Natural Resources/Water Series No. 22

# NON-CONVENTIONAL WATER RESOURCES USE IN DEVELOPING COUNTRIES

## PROCEEDINGS OF THE INTERREGIONAL SEMINAR
## WILLEMSTAD, CURAÇAO, NETHERLANDS ANTILLES
## 22-28 APRIL 1985

Department of Technical Co-operation for Development

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NOTE

Symbols of United Nations documents are composed of capital letters combined with figures. Mention of such a symbol indicates a reference to a United Nations document.

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FOREWORD

The United Nations has been involved in studies of desalination and other non-conventional water resources since 1965, when the Economic and Social Council adopted resolution 1069 (XXXIX), "Water desalination in developing countries." The United Nations Water Conference, held in Mar del Plata, Argentina, in March 1977, further recommended that research be promoted in weather modification, desalination and recycling of water, among others.

Over 20 years have passed since the United Nations published Water Desalination in Developing Countries,[1/] followed by a succession of several other publications on the subject. However, the subsequent sharp increases in the price of oil during the 1970s, with the resulting high costs for desalted water, acted as a damper on the installation of new units in non-oil-producing developing countries. The United Nations thus sharply reduced the scope of its work in the field in the mid-1970s.

It was therefore decided in the early 1980s to review the sector once again, expanding consideration to a broader range of sources of water supply, all of which currently carry the label "non-conventional". This resulted in a volume entitled The Use of Non-conventional Water Resources in Developing Countries, Water Series No. 14,[2/] published in 1985, which covered desalination, transportation of water by tanker and iceberg, waste-water reuse and weather modification. The volume was also used as a background document for the Interregional Seminar on Non-conventional Water Resources Use in Developing Countries, held at Willemstad, Curaçao (Netherlands Antilles) from 22-26 April 1985.

The 46 technical papers presented to that seminar were considered to be exceptionally good, and therefore it was decided to publish the Proceedings of the Seminar in the present volume. It is suggested that the two volumes (Water Series No. 14 and the Proceedings) be considered as companion volumes to be consulted by any country contemplating the use of non-conventional sources of water.

The topics included in the two volumes are slightly different. Both contain detailed information on desalination, transportation of water by tanker, waste-water reuse and weather modification. The earlier volume concentrates on research and background, while the Proceedings presents mainly case studies. In addition, the Proceedings includes two sections on rain-water harvesting and brief reviews of other subjects not contained in the earlier volume (i.e., dual water systems, use of drainage water for irrigation, boron pollution). The Proceedings contains over 20 papers describing actual experiences with non-conventional water resources in developing countries. These are considered a major contribution to work in this field.

The Department is indebted to O.K. Buros and Peter Hadwen for their valuable technical assistance at the Seminar and in the preparation of the present text.

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1/ United Nations publication, Sales No. 64.II.B.5.

2/ United Nations publication, Sales No. E.84.II.A.14

## EXPLANATORY NOTES

The following symbols have been used in the tables throughout the report:

Three dots (...) indicate that data are not available or are not separately reported.

A dash (--) indicates that the amount is nil or negligible.

A blank indicates that the item is not applicable.

Details and percentages in tables do not necessarily add to totals, because of roundings.

The following apply throughout the text and tables:

A full stop (.) is used to indicate decimals.

A comma (,) is used to distinguish thousands and millions.

Reference to gallons indicates United States gallons, and to "dollars" ($) United States dollars, unless otherwise stated.

Annual rates of growth or change, unless otherwise stated, refer to annual compound rates.

Surname and dates in parentheses () are keyed to reference lists following the individual papers.

The views expressed in signed articles are those of the authors and do not necessarily reflect those of the United Nations.

The designations employed and the presentation of the material in the present publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of the frontiers or boundaries.

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CONTENTS

PART THREE
COUNTRY AND REGIONAL PAPERS

Page



List of tables

Page

Page



## List of figures

Page

Page

## List of maps

## CONVERSION FACTORS

| To convert from: | To: | Multiply by: |
|---|---|---|
| mm | in. | 0.039 |
| cm | in. | 0.394 |
| m | ft | 3.281 |
| km | mi | 0.621 |
| km | NM | 0.540 |
| ha | acre | 2.471 |
| $cm^2$ | sq in. | 0.155 |
| $m^2$ | sq ft | 10.764 |
| $km^2$ | sq mi | 0.386 |
| l | US gal | 0.264 |
| $m^3$ | US gal | 264.2 |
| $m^3$ | Imp gal | 220.0 |
| kg | lb | 2.205 |
| metric ton | lb | 2,205. |
| metric ton | short ton | 1.102 |
| metric ton | long ton | 0.984 |
| $\$/m^3$ | $/1,000 gal | 3.785 |
| $\$/m^3/d$ | $/gpd | 0.004 |
| cm/s | ft/s | 0.033 |
| m/s | ft/s | 3.28 |
| m/s | mph | 2.237 |
| $m^3/s$ | US gal/m (gpm) | 15,850. |
| l/s | gpm | 15.850 |
| kW | 1,000 cal/min | 14.34 |
| kW | hp | 1.341 |
| kW | shp | .734 |
| kW | Btu/min | 56.88 |
| thousand joules | Btu | 0.948 |
| thousand joules | Wh | 0.278 |
| kWh | Btu | 3,413. |
| kWh | MJ | 3,600. |
| kWh | 1,000 cal | 860. |
| kg/MJ | lb/1,000 Btu | 2.331 |
| $kg/cm^3$ | psi | 14.223 |
| $kg/cm^2$ | atm | 0.968 |
| $kg/m^3$ | lb/gal | 0.008 |
| atm | psi | 14.7 |
| $kWh/m^3$ | kWh/1,000 gal | 3,785. |
| $m^3/d$ | gpm | 0.183 |
| $m^3/d$ | 1,000 gpd | 0.264 |
| $N/m^2$ | 1,000 psi | 0.145 |
| degrees celsius ($^oC$) | Fahrenheit ($^oF$) | $^oF=1.8^oC+32^o$ |
| ppm | $g/m^3$ at $15^oC$ | 0.999 |

## ABBREVIATIONS

The following abbreviations of organizations or territorial entities are used in this publication:

| | |
|---|---|
| ALDEP | Arable Lands Development Programme (Botswana) |
| APUA | Antigua Public Utilities Authority |
| AWWA | American Water Works Association |
| BDD | British Development Division |
| BVI | British Virgin Islands |
| CEA | Commissariat à l'Energie Atomique (France) |
| CEPIS | Centro Panamericano de Ingenieria Sanitaria y Ciencias del Ambiente |
| CIDA | Canadian International Development Agency |
| CPA | Canal de Provence Authority |
| CSC | Commonwealth Science Council |
| DIGAASES | Dirección General de Aprovechamiento de Aguas Salinas y Energía Solar (Mexico) |
| DRI | Drainage Research Institute (Egypt) |
| DTCD | United Nations Department of Technical Co-operation for Development |
| GCC | Gulf Co-operation Council |
| GTZ | Deutsche Gesellschaft für technische Zusammenarbeit (German Agency for Technical Co-operation) |
| IDA | International Desalination Association |
| IDEA | International Desalination and Environmental Association |
| IDRC | International Development Research Council (Canada) |
| IMO | International Maritime Organization |
| ITDG | International Technology Development Group |
| ITINTEC | Instituto de Investigación Tecnologica Industrial y de Normas Tecnicas (Peru) |
| IWSA | International Water Supply Association |
| JDF | Jamaica Defence Force |
| KAE | Kompania di Awa i Elektrisidat di Karsou (Curaçao) |
| NOAA | National Oceanic and Atmospheric Administration (United States of America) |
| OSW | Office of Saline Water (United States) |
| OWRT | Office of Water Research and Technology (United States) |
| PAHO | Pan-American Health Organization |
| PDA | Population and Community Development Association (Thailand) |
| PEP | Precipitation Enhancement Programme |
| PMA | Port of Marseilles Authority (France) |
| SAREC | Swedish Agency for Research Co-operation with Developing Countries |
| SERPAR | Servicio de Parques (Peru) |
| SOLERAS | Saudi Arabia-United States Joint Desalination Project |
| SWCC | Saline Water Conversion Corporation (Saudi Arabia) |
| TCI | Turks and Caicos Islands |
| UNA | Universidad Nacional Agraria (Peru) |
| UNDP | United Natons Development Programme |
| UNICEF | United Nations Children's Fund |
| USAID | United States Agency for International Development |
| USVI | United States Virgin Islands |
| WHO | World Health Organization |
| WMO | World Meteorological Organization |
| WSIA | Water Supply Improvement Association (United States) |

The following technical abbreviations are used in this publication:

| | |
|---|---|
| ABS | alkyl-benzene-sulphonate |
| AgI | silver iodide |
| atm | atmosphere |
| $BOD_5$ | biochemical oxygen demand after five days |
| Btu | British thermal unit |
| $^oC$ | degrees (Celsius) |
| cm | centimetre |
| COD | chemical oxygen demand |
| dwt | dead weight ton |
| ED | electrodialysis |
| EDR | electrodialysis reversal |
| $^oF$ | degrees (Fahrenheit) |
| FOB | free on board |
| GAC | granular activated carbon |
| GOR | gained output ratio |
| gpd | gallons per day |
| gpm | gallons per minute |
| HFF | hollow fine fibre |
| HTME | horizontal-tube multiple-effect |
| Igpd | Imperial gallons per day |
| J | joule(s) |
| k | kilo (one thousand) |
| kgal | thousand gallons |
| kJ | kilojoules |
| kW | kilowatt(s) |
| kWh | kilowatt hour(s) |
| l | litre(s) |
| LAS | long-chain benzene sulphonate |
| lb | pound(s) |
| LOT | load-on-top |
| LTV | long tube vertical |
| m | metre |
| MBAS | methalene blue active substances |
| MEB | multiple-effect boiling |
| MED | multiple-effect distillation |
| $m^3/d$ | cubic metres per day |
| mgd | million gallons per day |
| mg/l | milligrams per litre |
| mm | millimetre(s) |
| MPN | most probable number |
| MSF | multi-stage flash |
| MSS | multi-spectral scanning |
| NM | nautical miles |
| $NH_3$-N | ammonia nitrogen |
| $NO_3$-N | nitrate nitrogen |
| O&M | operation and maintenance |
| PCT | powdered carbon treatment |
| ppm | parts per million |
| PR | performance ratio |
| psi | pounds per square inch |
| psig | pounds per square inch guage |
| PVC | polyvinyl chloride |

| | |
|---|---|
| RBC | rotating biological contactor |
| RO | reverse osmosis |
| RPM | revolutions per minute |
| RVS | radar-volume-scan |
| ST | submerged tube |
| SWRO | sea-water reverse osmosis |
| TDS | total dissolved solids |
| TKN | total kjeldahl nitrogen |
| TOC | total organic carbon |
| TSS | total suspended solids |

# Part One

# REPORT OF THE SEMINAR

# I. REPORT OF THE SEMINAR

The Interregional Seminar on Non-conventional Water Resources Use in Developing Countries was held in Curaçao, the Netherlands Antilles, from 22 to 26 April 1985. The seminar was jointly organized by the United Nations Department of Technical Co-operation for Development (DTCD), the Government of the Netherlands Antilles and the Island Government of Curaçao. The major agenda items to be discussed related to progress achieved over the last 20 years in the fields of desalination, transportation of water by tanker, waste-water reuse, weather modification (cloud seeding) and rain-water harvesting. The seminar was attended by approximately 125 participants and observers, representing 36 countries and territories and 10 international organizations and agencies. The list of participants is attached as annex I to this report.

The seminar was opened by Prime Minister Maria Ph. Liberia-Peters of the Netherlands Antilles, who reviewed the importance of non-conventional water resources to developing countries, with particular reference to the Netherlands Antilles and Curaçao. She noted that the earliest land-based desalination facility had been constructed at Curaçao in 1928 and that the Netherlands Antilles had considerable experience with rain-water harvesting, desalination, windmill pumps, waste-water reuse and transportation of water by tanker. She drew attention to the role of non-conventional water resources in the International Drinking Water Supply and Sanitation Decade (1981-1990) and the crucial relationship between the provision of clean water and proper sanitation facilities and the health of population throughout the world. She also emphasized the precariousness of water resources development in small island countries with arid climates, and made a special plea for international assistance in such cases.

Mr. Bryan Locke, United Nations Development Programme (UNDP) Acting Resident Representative for the Netherlands Antilles, welcomed participants on behalf of the United Nations and gave an overview of UNDP's water and sanitation projects in developing countries, especially in the Caribbean region. He traced the early work of the United Nations in the field of desalination in the early 1960s, and noted that water-short countries which have to utilize such technologies should be aware of the alternatives available and their costs. Many Caribbean island communities were isolated and remote and many had extremely limited supplies of fresh water. In arid coastal areas, non-conventional water resources had offered an expensive but increasingly reliable solution to problems of water scarcity. Some of the factors which must be kept in mind when embarking on a programme involving non-conventional water resources were operation and maintenance and the importance of training skilled manpower to operate the plants.

Mr. Locke then enumerated some of the programmes being carried out jointly by the UNDP and the World Bank in support of the International Drinking Water Supply and Sanitation Decade. The principal focus had been on research, development and demonstration of low-cost technologies. In closing, he emphasized the importance of technical co-operation among developing countries through exchange of knowledge and experience at the seminar.

Mr. Enzo Fano, representing the United Nations Department of Technical Co-operation for Development (DTCD), provided some background on the role of non-conventional water resources in development and traced the progress in the field over the preceding 20 years. He described the early work of the United Nations in desalination and illustrated the conditions under which desalination would probably be technically and economically feasible. He noted progress in the main desalination technologies, particularly reverse osmosis of sea water. While the technologies had become increasingly reliable, the costs unfortunately remained beyond the reach of most developing countries.

Prospects for transporting water by tanker had improved in recent years, since there was currently a surplus of tankers available at very low costs as a result of the oil glut. The reuse and recycling of used water particularly for agricultural irrigation and industry had been advocated in recent years in order to reduce pollution and conserve water. As for weather modification, the intensive research which had been carried out on cloud seeding over the last 20 years had not yet provided conclusive evidence of the effectiveness of the method for increasing water supplies.

He concluded by pointing out that there was no single non-conventional solution which would be applicable to all areas. Each locality would have to review very carefully its own situation to determine, on a technical and economic basis, whether any non-conventional solution would be appropriate under existing cirmustances. Requirements for non-conventional water resources should be reviewed in the framework of water resources plans, within the context of the International Drinking Water Supply and Sanitation Decade.

The introductory session was followed by eight technical sessions dealing with the various types of non-conventional water resources: desalination, transportation of water by tanker, waste-water reuse, weather modification, and rain-water harvesting. All participants had been supplied with DCTD's background document, Water Series No. 14, entitled "The Use of Non-conventional Water Resources in Developing Countries" (ST/ESA/149, Sales No. E.84.II.A.14), which provided a comprehensive overview for the technical sessions. The programme of the meeting is presented in annex II of this report.

A total of 48 technical papers were submitted by experts and country representatives, relating to the main topics of the seminar. Most of these papers were presented at the technical sessions, and lively discussions concluded each meeting. Most of the technical papers are included in Parts two and three of this volume.

Three working groups were held on the morning of the final day of the seminar. These covered the following topics: technical aspects of desalination; technical aspects of non-conventional water resources other than desalination; and economic and institutional aspects of non-conventional water resources. The conclusions of those three working groups were presented at the final session and are summarized below.

The Seminar was closed by the Director of Public Relations, Mr. Roberto Suriel, who, on behalf of the Island Government, invited the United Nations to organize another meeting of the same type in Curaçao in 1988, to celebrate the 60th anniversary of the island's desalination plant.

## II. CONCLUSIONS OF THE SEMINAR

### A. Conclusions of working group 1: Technical aspects of desalination

#### Introduction

This conference, organized by the United Nations Department of Technical Co-operation for Development in collaboration with the Government of the Netherlands Antilles, was most timely, coming at the midpoint of the International Drinking Water Supply and Sanitation Decade.

The working group had been set up by the seminar to consider the application of desalination as a non-conventional source of water for developing nations and suggest criteria for its successful application. It was hoped that this report and the proceedings of the seminar would form a useful reference for developing countries in forming their water policies with regard to desalination.

#### 1. Water management policy

It was the recommendation of the group that the application of desalination to develop previously unusable brackish and sea water as sources of potable water should be taken within the context of a master plan for water resources development. In such a plan, the use of this relatively expensive water treatment process should be entered into with caution, after the possibility of utilization of more conventional and possibly less expensive sources of water had been carefully weighed.

The master plan should include measures for the optimum exploitation of natural resources. Steps should be taken to ensure rational use of water and minimize wastage. Water quality should be maintained at acceptable levels, and an appropriate pricing policy should be established. Public awareness and understanding of the policy on control and use of water should be ensured, and legislation should be enacted to back it up.

#### 2. Reliability

Once the decision was taken that desalination was required, the next consideration was reliability. Considering the crucial role of water for life and the high capital investment involved, a high reliability must be realized in order to meet and maintain the water requirements of the locality or the application. In most cases, this would involve the use of proven technology.

#### 3. Infrastructure

The necessary infrastructure must be examined and provided for before a plant would be built. Serious consideration should be given to such matters as the quantity and quality of feed water; disposal of brine and other materials during the life of the plant; the supply of energy and/or fuel to the site; and necessity for cooling media where required. Arrangements should be made to provide spare parts and consumables and to organize manpower resources. The new plant should be integrated within the already existing facilities, especially the water storage and distribution system of the locality. The existing infrastructure might determine the type of process and the type and extent of financing necessary.

## 4. Technical aspects

In connection with some of the more important technical aspects listed by the group, it was stressed that qualified technical expertise should be utilized at each appropriate stage of planning, design, construction and operation.

Technical considerations should include the following:

(a) The size of the plant would generally be dictated by water requirements and financial considerations. Modular construction should be an important option.

(b) The type of process chosen should preferably be a proven one.

(c) Sophistication should be the the least possible for safe, efficient, economic and reliable operation of the plant, and at the same time consistent with the skill of the personnel and training available.

(d) Infrastructure and reliability should be considered, as mentioned above.

(e) Capital availability and financing would be of primary importance.

## 5. Current technology

Current technology was available so that, with proper design, construction and operation, desalination of sea water could be accomplished using the distillation and reverse osmosis processes, while brackish water could be desalted by the electrodialysis and reverse osmosis processes. All of these technologies had proved to be reliable under reasonably good infrastructure and manpower conditions.

## 6. Manpower planning and technical training

Manpower planning should be the basis for human resources development to manage, operate and maintain the desalination plants. Co-operation among developing countries concerned with non-conventional water resources might be emphasized on a regional scale. Sharing of knowledge among plant users and interchange of known field experiences should be encouraged.

### 7. Technology transfer

The transfer of technical information was of importance to ensure sustained improvements in desalination technology and its application. Since developing countries generally lacked a broad technological infrastructure, technical co-operation among users and manufacturers should be encouraged, as that would be beneficial to both sides.

### 8. Village desalination technology

For villages in developing areas, certain small-scale desalination facilities based on existing commercial systems might not always be appropriate for successful application.

Therefore, other desalination methods should be researched and investigated. Among the processes that could be studied might be: (a) improved simple solar stills; (b) liquid-liquid solvent extraction; (c) salt precipitation; (d) freezing (for colder areas); and (e) other simple systems.

Any process developed should stress reliability, low energy usage, ease of operation and use of locally available materials. When possible, renewable energy options, including solar and wind power, should be explored for small village desalination units.

### Conclusion

Desalination had proved to be a viable method of producing fresh water from brackish and sea water sources. The use of desalination should be entered into with caution and after careful consideration of its use and applicability as a supplement or substitute for conventional water sources. Developing countries were strongly advised to seek advice from other developing countries more experienced in the field.

## B. Conclusions of working group 2: Technical aspects of non-conventional water resources other than desalination

### Introduction

The group considered five non-conventional sources of water: transport of water by barge and tanker; non-potable water flushing and dual systems; waste-water treatment and reuse; rain-water harvesting; and weather modification.

On several occasions during the discussions, the importance of water conservation and of prevention of waste had been stressed. The prevention of water wastage should be given prominence in water resources planning.

The group recommended that a single authority in any country or large area should plan and manage all water resources, their use, waste-water treatment and reuse.

## 1. Transport of water by tanker and barge

The transport of water had to be considered under two headings:

(i) Transport of water as backhaul along the main oil tanker routes of the world, which had been identified as being from the Persian Gulf to Europe, North America, and Asia;

(ii) Transport of water to countries and islands off the main tanker routes.

### Conclusions

(a) The backhauling of potable and non-potable fresh water from the oil-receiving ports to the Gulf appeared to have merit and should be investigated. These investigations should include specific cost data, guarantees on the continuity of supplies, and the adequacy of loading and unloading facilities. Port facilities would be important, as tankers required rapid discharge capability in order to minimize costs.

(b) Transporting water outside the main oil shipping routes should only be selected as an alternative to developing the area's natural water resources after very careful study, for the following reasons:

(i) It could require a continuous expenditure of foreign currency;

(ii) The arrangement subjected the receiver to external forces outside his control, such as shipping strikes, weather, etc.;

(iii) It was likely to prove more expensive than developing the natural resources.

(c) It was essential that shipping companies offering to transport water outside the main tanker routes provide reliable, firm data on costs and conditions, such as the required minimum quantities, rates of discharge and discharge facilities, storage and channel draft. Such information would be needed if developing countries were to give barging serious consideration as a firm source of supply.

(d) With regard to barging water to areas off main tanker routes, that approach appeared to have merit during emergency drought periods. Countries which suffered periodic droughts should consider provisions for barge off-loading facilities, including storage, as components of their distribution systems.

(e) There appeared to be scope for international co-operative programmes on transporting water where small islands were involved.

(f) Assuring the purity of transported drinking water was essential; adequate laboratory and treatment facilities must be available to test tankered water and provide necessary treatment before it was introduced within a supply system.

## 2. Dual systems

Sea water and brackish water were used in several countries for non-potable purposes, such as sanitary flushing, by using dual distribution systems over a large area or within individual premises. Such dual systems could supplement limited potable supplies to good advantage.

### Conclusions

(a) Sea water could provide an economic alternative to the use of potable water for sanitary flushing where potable water is limited and costly.

(b) Sea water should be screened and disinfected to prevent marine growth in pipes and fittings.

(c) Shoreline boreholes would be preferable to direct sea-water intakes, so as to minimize suspended solids in the sea water.

(d) The use of plastic and fibreglass pipes and cisterns could minimize corrosion problems.

(e) In sea and brackish water distribution systems, attention must be given to the potential problem of underlying aquifers becoming saline or polluted due to leaking mains and cess pit discharges.

(f) For individual households or businesses located above brackish ground-water sources, the use of ground water for non-potable purposes should be encouraged.

## 3. Waste-water treatment and reuse

In areas where waste water is collected in a sewerage system, the waste water could provide a valuable source of non-potable water when treated to appropriate levels.

### Conclusions

(a) Treatment of sewage effluent was essential.

(b) Basic technology, such as stabilization ponds, was available at low capital and operating costs for the treatment of sewage effluent, and could provide irrigation water at a relatively low cost in many instances. It was essential that the proper retention time for the waste water in the stabilization pond be strictly observed to ensure a high level of purification.

(c) Legislation and regulations to control treatment and use were essential.

(d) Water supply, sewage treatment and reuse should be managed as a whole.

(e) Some type of sewage effluent treatment, irrespective of the need for irrigation, should be provided to protect surface- and ground-water resources, especially where these were used for drinking water supplies.

(f) Caution was necessary in the use of treated sewage water for irrigation. Treated waste water should not be used for root crops or vegetables eaten raw until it was reliably shown that such water could be used without risk for such crops.

(g) Considerable land area was necessary for properly-designed stabilization ponds. If the water were to be used for agriculture, the ponds should be located near to end-users.

## 4. Rain-water harvesting

The discussion focused on individual roof catchments, and there was ample evidence that such catchments were being used successfully in several countries to provide safe supplies of potable water.

### Conclusions

(a) For catchment systems to be successful, there must be adequate rainfall, reasonably spread throughout the year and a clean atmospheric environment.

(b) The major cost incurred in providing a roof catchment water supply was the cost of the storage facilities. It was felt that the United Nations could survey the types of storage cisterns in use and being constructed in many parts of the world. Information on low-cost standardized storage systems could be collected and the results of the investigation could be published.

(c) The cost of water storage could be reduced for community housing developments by the use of one or more central storage tanks.

(d) Where conventional water supplies were limited, rain-water harvesting and storage should be encouraged, even in some cases where piped water was available.

(e) Sub-surface dams could be used as large rain-water catchments to supply potable and agricultural water to rural and semi-urban populations of many developing countries.

## 5. Weather modification

It was debatable whether weather modification should fall under the heading of a non-conventional water resource. Nonetheless, the Group reached certain conclusions.

Conclusions

(a) A developing country should not rely on weather modification until it had exhausted the development of its natural water resources and still needed more water.

(b) Weather modification might be considered a supplementary water source in long-term planning.

(c) Great caution was necessary in considering the use of weather modification techniques.

(d) The United Nations should be encouraged to carry out a worldwide survey of the prospects for weather modification.

(e) Information on how to carry out preliminary local studies should be developed and circulated to developing countries.

(f) The potential of weather modification to extend periods of rain or rainy seasons appeared to be the most immediate practical use of weather modification.

(g) The international community should give consideration to and study weather modification, particularly the technical and legal aspects.

## C. Conclusions of working group 3: Economic and institutional aspects of non-conventional water resources

Introduction

On economic aspects of non-conventional water resources, group 3 spent considerable time identifying the major and most sensitive cost components of the various non-conventional technologies. The group concluded that there was a need for an economic/financial study to analyze and define cost factors of the various options, including desalination processes, transportation of water by tanker or barge, rain-water harvesting, waste-water reuse and particularly weather modification.

The group identified dominant cost factors and estimated ranges of possible costs for the various technologies. It concluded its work by preparing a table which listed reasonable minimum cost targets for large-scale production of water (greater than 5,000 $m^3/d$), using non-conventional water resource techniques. In addition, a list was made of economic and other factors which must be taken into account in planning for a non-conventional water resource application. One dominant cost factor for all forms of water resource development was financing for capital expenditures. The nature of the financing, including the period for payments, the need for foreign exchange and the finance charges (interest) all affected the financing cost factor. Because financing was common to all types of water resources development, advance financing had been left out of the list of dominant cost factors which follow.

## 1. Desalination

With current technologies, all three major desalination processes (reverse osmosis, electrodialysis and distillation) were competitive under certain circumstances. It was recommended that for general cost comparisons of desalination systems, The USAID Desalination Manual and the United Nations Water Series No. 14 guidelines be used.

### Dominant cost factors in desalination

- (a) Energy
- (b) Capital recovery factor
- (c) Overheads, operation and maintenance costs, parts replacement
- (d) Labour
- (e) Plant factor
- (f) Environmental and on-site factors

It was recognized that desalination of brackish water would be considerably less expensive than sea-water desalting due to the savings in energy costs, but that disposal of brine at an inland site where brackish water was commonly found could create a costly environmental problem. Adequate management and competent operation and maintenance personnel could reduce costs substantially, but good examples were few in developing countries.

## 2. Transportation of water by tanker and barge

A table was prepared which summarized the main cost factors for water transportation, depending on the use of the water to be transported and the type of service that would supply the water, as follows:

### Dominant cost factors for water transported by barge or tanker

| Shuttle service | Segregated ballast tanks | Cargo ballast |
|---|---|---|
| | Potable | |
| (a) Transportation | (a) Facilities both ends | |
| (b) Facilities at loading and receiving ports | (b) Treatment both ends | |
| (c) Treatment both ends | (c) Cost of water at loading port | |
| (d) Cost of water at loading port | (d) Transportation costs involved in diversion from main transportation route or extra time in port | |

| Shuttle service | Segregated ballast tanks | Cargo ballast |
|---|---|---|
| | Non-potable | |
| (a) Transportation | (a) Facilities both ends | (a) Diversion from main transportation route |
| (b) Facilities both ends | (b) Partial treatment | (b) Cost of water at loading port |
| (c) Partial treatment | (c) Cost of water at loading port | (c) Facilities both ends |
| | (d) Diversion from main transportation route | (d) Treatment |

The key to low costs for water transported by tanker or barge was to transport large quantities using large tankers on a long-term, continuous basis. This significantly reduced the unit cost. However, for this type of transport to be effective, there must be proper and very efficient loading and unloading facilities. If these did not already exist, they could be very expensive to construct.

It was concluded that the backhaul of non-potable water along the main tanker transportation routes to the Persian Gulf or other sites might have merit, as costs of water delivered would be competitive with sea-water desalination. Shuttle transport of water between small islands was found to be expensive on a unit price basis. Moreover, in certain cases island importers would need site-specific cost data and a guarantee of continuity of supply if they were to depend on such sources. Barging supplies of water often was most appropriate for consideration under emergency situations.

### 3. Waste-water reuse

When discussing the economics of waste-water reuse, the main factors to be considered were identified and are presented below.

Dominant cost factors in reclaiming waste water for agricultural or industrial applications

(a) Treatment facilities -- capital cost
(b) Operation and maintenance -- labour, spare parts and energy
(c) Land
(d) Sewage collection system

The group noted that under appropriate circumstances waste water could be economically attractive for agricultural irrigation and non-potable industrial purposes. Problems with this source of water were related as much to health and cultural factors as to economics. However, the results of a large number of projects indicated the importance and feasibility of waste-water reuse with a minimum of health risks. The group concluded that in most cases reuse of waste water presented the cheapest non-conventional water resource technique.

## 4. Rain-water harvesting

The group considered individual roof catchments and larger communal catchments from airport runways, institutional roofs or other limited watersheds. The main cost factors were identified as follows:

| Roof catchments | Communal catchment |
|---|---|
| (a) Capital cost of appropriate roof and tank | (a) Land and construction |
| (b) Labour -- contractual, self help | (b) Operation and maintenance -- labour |
| (c) Operation and maintenance | (c) Treatment |

The group recognized that individual rain-water catchment tanks were a traditional source of water in many countries and that traditional self-help systems had evolved in many communities to build such tanks for one or more families. In one country, an official revolving fund had been established by a non-governmental organization to provide capital for individual tanks with capacities of about 11 $m^3$. These tanks were constructed by the people of the community. The system was considered a positive example of resource mobilization at the community level. However, costs of investment per capita were generally higher than other low-cost options for rural water supply. Costs were dependent on the size of the storage relative to the rainfall and the desired level of reliability.

## 5. Weather modification

The group found it difficult to assess the costs of weather modification. However, it was clear mainly from experiments in Israel that, under certain meteorological conditions, artificial precipitation could produce water at very low costs in comparison with other non-conventional sources. The main cost factors could be identified as follows:

(a) Flying costs for cloud seeding -- capital, operation and maintenance
(b) Scientific equipment
(c) Salaries for scientists and pilots
(d) Seeding agents and flares

The group recognized that, when conditions were suitable, weather modification could probably provide an inexpensive source of water through increased precipitation over a wide area. However, scientific verification was necessary at each site to determine whether a project was actually beneficial. Few cloud seeding experiments had included a rigorous economic evaluation, nor were detailed economics formally included in the designs.

## 6. Summary of costs

On the basis of a few success cases of state-of-the-art technology, the following minimum costs were set by the Group as attainable targets:

Minimum cost targets for water at plant gate from non-conventional technologies

| System | Range of minimum cost/m3 | Average minimum |
|---|---|---|
| Sea water distillation | \$1.10 - \$1.50 | 1.40 |
| Sea water RO | \$1.10 - \$1.40 | 1.20 |
| Brackish water RO | \$0.15 - \$0.70 | 0.40 |
| Transport by tanker | \$2.00 - \$2.50 | 2.30 |
| Reclaimed waste water | \$0.15 - \$0.40 | 0.25 |
| Roof/catchment | Roof \$4.00-\$8.00/$m^3$<br>Catchment \$1.00-\$1.50/$m^3$ | |
| Weather modification | Very low cost per $m^3$; perhaps \$1.00-2.00/season/ha | |

## 7. Other economic considerations

Economic issues related to potable supplies which might be considered by governments included the following:

(a) Pricing policies: Tariffs could be levied on the basis of steep progressive rates, with subsidies for the very poor and special rates for the promotion of industry. Major considerations should include sustainability of the operation (i.e., cost recovery) and elimination of water wastage.

(b) Consumer categories: Differential tariffs could be levied for large, medium and small or rural consumers. One of the considerations that needed to be included in setting rates should be the incremental costs involved in supplying water to various categories of consumers. In some areas, large consumers provided for an important part of the base load, which tended to reduce costs. In other areas, they may force utilities to develop higher-cost supplies of water.

(c) Mobilization of resources at the community level: Collection of fees for operation and maintenance, community contributions of labour and materials and revolving fund mechanisms should be considered at the local level.

(d) Emergency supply by transport: In certain specialized cases, governments might consider acquiring a large tanker under current favourable economic conditions to service emergencies and/or to use for storage of water.

(e) Shutting off uneconomic desalination systems: The economics of retiring or modifying old desalination plants should be studied, as energy and operation and maintenance costs might be higher than total costs of a newly installed desalination plant.

## 8. Institutional and social aspects

It was recognized that social and institutional aspects were closely linked in the provision of water supply. The following were essentially non-economic issues which must be taken into account when introducing a non-conventional water resource to a community.

(a) Self-reliance: Reliability, top quality materials, training for operation and maintenance, and high standards should be considered to ensure continuous water supply and avoid emergency situations.

(b) Potential mix of supplies: For base and peak loads a combination of supplies could offer flexibility to water utilities under different conditions.

(c) Social and political aspects of transporting water by tanker or barge: Countries might not want to depend on transporting water from outside sources for long-term supply as this required continuous expenditure of foreign exchange and could be subject to the vagaries of international politics.

(d) Unaccounted-for water: Widespread leakages and illegal connections often accounted for 30 to 50 per cent of water entering the distribution system. A systematic programme of accounting for water in the distribution system, leak detection, and identification of unmetered connections would be economically beneficial to the water utility, and should be enforced.

(e) Quality issues: Health considerations were of primary importance in waste-water reuse schemes. Corrosion or malfunctioning of post-treatment systems in multi-stage flash (MSF) and reverse osmosis (RO) plants could produce water of unacceptable quality. Taste was also an important factor in the acceptability of new sources of water. It was necessary to monitor carefully the quality of non-conventional water resources used.

(f) Management of water resources: It was recommended that one authority or agency be responsible for planning and co-ordination of all water resources. The ownership of an individual water supply system should be clearly defined and responsibility allocated, whether individual or collective.

(g) Social and political aspects: The following types of issues must be considered: availability of labour, fuel and spare parts; effect on the community and the environment of a new system; dependency on outside sources of labour and water; expenditures of foreign exchange; community acceptance of and responsibility for a new water supply system; change in cultural patterns resulting from a change in water supply; and allocation of water and charges among users.

(h) Conservation promotion: It was necessary to make the population aware through education programmes of the importance of conserving limited water resources. Public co-operation in reducing use could contribute greatly to increasing efficiency of use and saving costs of developing expensive non-conventional water supply systems. Rules and regulations to promote efficient use of water and to minimize wastage were essential when a country, region, or city reached the point where non-conventional sources had to be integrated into its water supply system.

Annex I

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## Annex II

### FINAL PROGRAMME

21 April - Sunday

| | | |
|---|---|---|
| 3:00 | Registration | |
| 6:00 | Registration ends | |

22 April - Monday

| | | Speaker |
|---|---|---|
| 8:30 | Late Registration | |
| 9:00 | Introduction and welcome | H.E. M.Ph. Liberia-Peters<br>Prime Minister, Neth. A.<br>B. Locke |
| | The role of non-conventional water resources in development | E. Fano |

Session 1: The role of non-conventional water resources in developing countries.

| | | |
|---|---|---|
| 11:00 | An overview of non-conventional water resources in developing countries | M. Brewster |
| | An introduction to desalination | O.K. Buros |

Session 2: Desalination technology

| | | |
|---|---|---|
| 2:00 | Recent developments in reverse osmosis | P. Culler |
| | Recent developments in electrodialysis | A. Pang |
| | Recent developments in distillation | M. Lucas<br>D. Hoffman |
| 4:00 | Desalination with renewable energy sources | T.A. Lawand |
| | Support of village-level and small-scale systems | O. Perez Siller |
| 5:30 | Session ends | |
| 6:30 | Welcome cocktail party | |

23 April - Tuesday

Session 3: Desalination experience in developing countries

| | | |
|---|---|---|
| 8:30 | Experiences with desalination operation | D. Khumayyis<br>H. Gouverneur<br>H. Abouzaid<br>B.P.C. Sinha |
| 11:00 | Economics of desalination | J. Birkett |
| | Process selection for desalination systems | R. Silver |

| | | Speaker |
|---|---|---|
| **Session 4: Transport of water** | | |
| 2:00 | Innovative approaches to transportation of water by tanker: an overview | T.A. Meyer<br>J. Hargreaves |
| | European experiences with transporting water by tanker | F. Bonifacio<br>C. Wielenga |
| 4:00 | Caribbean experiences with transporting water by tanker | S. De Haan<br>S. Blackman |
| | Dual systems | H. Smith |
| 5:30 | Session ends | |
| **24 April - Wednesday** | | |
| **Session 5: Waste-water re-use** | | |
| 8:30 | An overview of waste-water re-use | J. De Boer |
| | Experiences with waste-water re-use in developing countries | C. Ertuna |
| | Waste-water re-use in industry | G. Pauthe |
| 11:00 | Health aspects of waste water re-use in agriculture | S. Arlosoroff |
| | Environmental and health aspects of re-use | F. Reiff |
| | Reuse of drainage water for irrigation | S. El-Gindy |
| 12:45 | Session ends | |
| 1:00 | Lunch Seaquarium (transportation by bus furnished) | |
| 3:00 | Field trip to desalination and other island facilities | Kompania di Awa i Elektrisidat (KAE) |
| 5:00 | Reception at the hotel | Courtesy of KAE |
| **25 April - Thursday** | | |
| **Session 6: Weather modification** | | |
| 8:30 | An overview of weather modification | A. Gagin |
| | Experiences and future potential for weather modification | L.R. Koenig |
| **Session 7: Rainwater harvesting** | | |
| 10:30 | Overview of rainwater harvesting | P. Hadwen |
| | African experiences with rainwater harvesting | H. McPherson |
| | Asian experiences with rainwater harvesting | P. Sornjitti |

| | | Speaker |
|---|---|---|
| **Session 8:** Application of non-conventional water resources use in developing countries | | |
| 2:00 | Appropriate technology for water resources development | P. Douard<br>M. Aseged<br>S. Khalaf |
| | Training of staff for operation and maintenance | |
| 3:40 | Case studies of non-conventional water resources use in developing countries | N. Thomas<br>B. Mahbub<br>S. Theodosiou<br>K. Sparkes<br>X-T. Song |
| 6:00 | Session ends | |
| 8:00 | Buffet dinner and folkloric show | |

26 April - Friday

Session 9: Working group meetings

Three working groups will be formed. Each group will discuss a separate topic. The topics to be discussed are:

1. Technology aspects of desalination
2. Technology aspects of other non-conventional water resources
3. Economic and Institutional aspects of non-conventional water resources

| | | |
|---|---|---|
| 9:00 | Working groups meet | |
| 11:00 | Working groups resume meeting | |

Session 9: Conclusions and recommendations

| | | |
|---|---|---|
| 2:00 | Plenary session - Reports of the three working groups | |
| 3:30 | Conclusions: guidelines for choosing among non-conventional alternatives | E. Fano |
| | Closing remarks | R. Suriel, Director of Public Relations, Island Govt. of Curaçao |
| 4:00 | Seminar ends. | |

Part Two

# TECHNICAL BACKGROUND PAPERS

## I. OVERVIEW OF NON-CONVENTIONAL WATER RESOURCES IN DEVELOPING COUNTRIES

by Marcia Brewster*

It is the objective of this paper to provide a brief overview of non-conventional water resources in developing countries, which arises essentially from the background document for this seminar, water series No. 14, the Use of Non-Conventional Water Resources in Developing Countries. Some of the major broad conclusions reached will be reviewed and then comparisons will be summarized among the four main non-conventional water resource technologies dealt with in that volume, desalination, transportation of water by tanker, waste-water reuse and weather modification (in this case referring to precipitation enhancement through cloud seeding). Two other technologies referred to in the volume, the transport of icebergs and the suppression of evaporation, are fascinating subjects, but extremely limited in terms of the technical and economic feasibility.

### A. Broad conclusions of the study

The first broad conclusion is that costs of any of these technologies are difficult to determine with accuracy and are not comparable from place to place. For example, costs of a unit of water produced by desalination, the technology with which we have the most experience, are very site-specific and can seldom be predicted or even calculated. Plant factor and operator skill level have as much a bearing on final costs as capital investment and energy prices.

Second, no single non-conventional solution is suitable to all water-short areas. Each locality must carefully examine its own situation to determine which, if any, non-conventional solution might be applicable. Much depends on the willingness of a community to accept and take responsibility for a new water project.

Third, in any situation where a conventional source of water can be developed, it will almost always be preferred to a non-conventional source. However, if conventional ground water or surface water supplies are inadequate, consideration should be given to some of the non-conventional water resource techniques presented in that publication, and at this seminar.

Fourth, the common characteristics of non-conventional water resources are that they are generally more complex in development and operation than conventional sources, and are almost always more expensive. Treatment of conventional supplies ranges from none at all to removal of suspended solids or hardness materials and generally costs less than $0.25/m$^3$. The cost per unit of water using non-conventional techniques on the other hand, exceeds, sometimes greatly, $0.25/m$^3$.

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Finally, selection and implementation of a non-conventional water project should be carried out with caution. None of the methods will provide magical solutions and most will require large capital expenditures and continued long-term support with additional funding, technical labour, spare parts, chemicals and continual attention to detail. In most cases they involve considerably more risk than conventional solutions. At the same time, by providing water to an arid area, non-conventional water resources may offer an opportunity for development previously considered impossible.

## B. Markets for non-conventional sources

The major markets in developing countries for non-conventional water resources are the Middle East and North Africa and islands of the Caribbean, Mediterannean and North Atlantic. Non-conventional water resources, aside from weather modification, are basically intended to assist countries with water shortages by supplying a specific small geographical area such as a town or a remote rural or coastal community with water. It is possible to repeat the installation or extend pipelines to distribute water over a relatively large region, however. Saudi Arabia is an example of a country that is heavily dependent on non-conventional water resource technology. It has utilized desalination to convert its large supplies of brackish and sea water into potable water, and provides by far the largest market in the world for desalination facilities. Desalination has been used to supply both individual locations and large regions. The latter are supplied by pipeline from large complexes built along the underdeveloped sea coast. The 1 million $m^3/d$ Al-Jubail desalting facility on the Persian Gulf is the largest in the world and produces water which is piped 485 km inland to the city of Riyadh.

Other Middle Eastern countries such as Bahrain, Kuwait, Qatar and the United Arab Emirates are also almost completely dependent on non-conventional water supplies. Like Saudi Arabia, these oil-exporters have ample capital resources, considerable experience with desalination, relatively cheap energy costs and relatively expensive water costs. Other developing countries, which have considerable experience with using non-conventional sources of water, are China, Cyprus, Egypt, Greece, India, Iraq, Jordan, Malta, Mexico, the Netherlands Antilles and the United States Virgin Islands. Industrialized countries such as Australia, the Federal Republic of Germany, France, Japan, the Netherlands, and the United States of America have been pioneers in the development of desalination, waste-water reuse and weather modification technologies. Norway and other European countries have conducted intensive research on the transportation of water by tanker. Israel provides an example of a country which has long experience with all the non-conventional technologies, including the use of saline water for agriculture.

## C. Comparison of non-conventional alternatives

Each of the non-conventional techniques discussed in the volume has various characteristics relative to technical, economic and practical feasibility. These are summarized in table 26 of Water Series No. 14 which is reproduced in table 1 below.

Costs. As can be seen from the cost data, desalination of brackish water can provide a relatively reliable source of water for costs ranging from \$0.25 to \$1.00/$m^3$. Desalination of sea water and water transported by tanker may provide water for costs of \$1.25 to \$8.00/$m^3$. Reused waste water gives us a lower quality water at a cheaper price, while weather modification has the potential to provide a low-cost, bur relatively unreliable, source of water.

Stage of development. Desalination is the only one of the technologies which could be said to have widespread experience and application, while reused wastewater is being increasingly used in various agricultural and industrial applications. Experience with transportation by tankers is limited, while weather modification is still in the experimental stage.

Special physical requirements. As far as special physical requirements are concerned, desalination requires a good source of feed water and a means to dispose of the brine solution. Transport of water by tanker requires port and storage facilities, a good source of fresh water and demand for water along a coastal area. Water reuse requires a source of waste water, which in developing countries may not be readily available. Cloud seeding requires suitable clouds and structures to store increased rainfall, and a scientific staff trained in the technology.

Advantages and disadvantages. Among the advantages of desalination are that it is a proven technology with relatively predictable costs and results. Water transported by tanker has the advantage of requiring only a low level of technology, and it can provide a quickly-implemented response to a temporary water shortage. Waste water reuse can take advantage of proven technologies, and costs and production are predictable. Only a moderate skill level is needed. Moreover, it provides a moderate cost alternative for non-potable applications and can reduce problems associated with pollution. Weather modification could supply water over a wide area, thus reducing distribution costs. Investment is relatively small and the technique could reduce arid conditions over a large area.

The disadvantages of desalination are that it is a very energy-intensive process, making it expensive to operate, and that it requires a high degree of technical skill for operation and maintenance. Delays in repair of equipment or improper maintenance can lead to damage of capital equipment. Moreover, it generally requires expenditures of scarce foreign exchange. Transportation of water by tanker requires large storage capacity, high capacity pumps and a deep water port for large vessels. Politically, the importer has to depend on outside sources of water and the vagaries of international politics. The main disadvantage of waste water reuse is that it may be unacceptable aesthetically or culturally and may involve health risks. With weather modification, there is no assurance of success because of the experimental nature of the technology. Results cannot easily be measured and the right types of clouds must be available. Infrastructure must be provided to take advantage of the additional rainfall.

In summary, various desalination processes including distillation, reverse osmosis and electrodialysis have proved to be commercially viable, reliable techniques for removing the salt from brackish and sea waters. In

Table 1. Comparison of non-conventional water resources: technical, economic and political criteria

| Criteria | Desalination | Transport-tankers | Water reuse | Weather modification |
|---|---|---|---|---|
| Representative costs | Cost of water (including capital recovery)<br>Brackish: 0.25-1.00/$m^3$ (0.95-3.80/1,000 gal)<br>Sea water: \$1.30-8.00/$m^3$ (4.90-30.30/1,000 gal)<br>Cost of water using renewable energy sources (based on total capital costs)<br>\$4.00-50.00/$m^3$<br>(15.00-190/1,000 gal) | Transportation<br>\$1.00-6.00/$m^3$<br>(3.80-23.00/1,000 gal)<br>Water at source<br>\$0.25-1.50/$m^3$<br>(0.95-5.70/1,000 gal)<br>Cost of water<br>\$1.25-7.50/$m^3$<br>(4.75-28.40/1,000 gal) | Cost of water<br>\$0.07-1.80/$m^3$<br>(0.30-6.85/1,000 gal) | Costs of application<br>\$1.50-5.00/ha/season<br>Costs of water (based on Israeli estimates of increased water supply)<br>0.01/$m^3$<br>(0.04/1,000 gal) |
| Stage of development | Moderate to high; widespread experience | Low to moderate; some experience | Moderate: experience in various areas | Low: still experimental |
| Special physical requirements | 1. Source of clean brackish or sea water<br>2. Method or place to dispose of a brine solution | 1. Reliable source of potable water in another area or country<br>2. A need for water adjacent to a port or coastal area<br>3. Port facilities to unload tanker<br>4. Large storage facilities | 1. Source of waste water | 1. Suitable clouds<br>2. Scientific staff<br>3. Structures and land use to take advantage of increased rainfall |
| Advantages: Technical | 1. Proven systems available<br>2. Cost of equipment and production could be reasonably predicted<br>3. Wide range of supplies | 1. Low level of technology required, except for initial investment in port facilities | 1. Proven techniques available<br>2. Cost of equipment and production could be reasonably predicted<br>3. Wide range of suppliers<br>4. Only a moderate technical skill level needed | 1. Can supply water over a wide area, thus reducing distribution costs<br>2. Only a moderate to small capital investment needed |
| Political | 1. Can develop own water resources | 1. Can provide a quickly implemented solution to a water shortage | 1. Can supply a moderate cost alternative for water used in non-potable applications<br>2. Can reduce problems associated with present method of waste-water disposal, including pollution | 1. Has the potential to reduce arid conditions over a large area |

| Criteria | Desalination | Transport-tankers | Water reuse | Weather modification |
|---|---|---|---|---|
| Disadvantages: | | | | |
| Technical | 1. Requires skilled technicians for operation and repair of equipment<br>2. Energy-intensive process<br>3. Delay in repair or lack of operating supplies can damage capital equipment | 1. Water arrives in large quantities necessitating high capacity pumps and large storage tanks to permit the tankers to unload quickly<br>2. Deep draught channels and facilities needed for large vessels | 1. Requires some skill in operation and maintenance of facilities<br>2. Improper operation could create the potential for adverse public health effects<br>3. Will only work in areas where waste water is collected | 1. Still in the research stage with many uncertainties<br>2. Requires scientific support<br>3. Cannot really control results<br>4. Must have infrastructure and land use to take advantage of additional rainfall |
| Political | 1. Generally requires use of foreign exchange to purchase equipment<br>2. Involves continual high energy usage | 1. Must depend on sources and transporters outside country. The potential for a supply interruption because of storms, conflicts, boycotts or strikes is relatively high<br>2. Can be expensive | 1. May not be aesthetically or culturally acceptable | 1. No assurance of success<br>2. Very difficult to measure or quantify success<br>3. Likely to be blamed for all problems with weather |
| Certainty of operation | High | High | High | Low to moderate |
| Typical applications for water | Potable<br>Industrial | Potable<br>Agriculture<br>Industrial | Agriculture<br>Industrial | Potable<br>Agricultural<br>Industrial |

the future, it can be expected that continued research and development of these techniques should reduce operating costs and improve reliability.

The future of tanker transport of water is less a matter of technology, which is relatively straightforward, and more a matter of economics under existing market conditions. The current excess capacity of very large tankers makes their use for water transport attractive, but that is a temporary situation, as surplus vessels are being sold for scrap and as the world's need for oil increases.

The future prospect for the widespread application of waste-water reuse in developing countries depends on several important factors. The first is the installation of waste-water collection systems to provide a source of waste water. The second will be further research into the long-term health implications of various applications of water reuse. Other factors include cultural acceptance and the desire to treat effluents to minimize pollution. The reclamation of waste water for certain agricultural and industrial purposes can be expected to increase in the future, where alternative sources of high-quality water are either unavailable or too expensive.

The many complex variables involved in weather modification will probably hinder its widespread application for increasing rainfall in most areas in the near future. However, it can be expected that as knowledge of weather patterns increases, the ability to make predictions as to appropriate seeding conditions will improve.

Prospects for wider application of non-conventional water resource techniques may thus have promise, mainly as the result of two factors. The first is that the reliability of many of these techniques should increase with further investigation and experience. The second is that the continued increase in population and per capita water use will put stress on existing supplies and increase the costs of developing sources and supplies by conventional means. This will provide opportunities for the economic application of non-conventional water resource techniques.

However, the selection and use of a non-conventional water resource technique should be done carefully with full recognition of the potential positive and negative implications of such a choice. While the best course of action for any area is to develop its low cost conventional water resources first, the increasing scarcity of such resources will drive up their costs, making non-conventional development economically feasible and necessary in the foreseeable future.

## II. DESALINATION

### A. An Introduction to Desalination

by O. K. Buros*

#### Background

Water is known as the universal solvent. As such, it plays a key role on our planet in supporting and sustaining both plant and animal life. The movement of water through the earthbound portion of the hydrologic cycle increases the concentration of dissolved materials, mostly salts, found in the solution. The transpiration and evaporation also increases this concentration.

There is a limit to the concentration of dissolved salts in water if it is intended for agricultural, potable, and most industrial uses. As this limit is exceeded, the water's value for these purposes is greatly diminished. The applications of saltier (brackish or saline) water then tend to be for the support of marine life and oceanic commerce.

Man's interface and use of the saline aqueous environment has been contingent on the concomitant availability of fresh water to support the previously discussed needs. Ocean-going commerce was historically restricted, owing to the necessity for fresh water for cooking and drinking. The development of settlements along the coasts or in other arid areas has been likewise tied to the availability of fresh water. In ships, this water was usually carried in tanks, while cities relied on nearby rivers or ground-water aquifers. If these sources were insufficient, long-distance pipelines were often used. The lack of sufficient nearby fresh water or financial resources to construct pipelines has meant that many otherwise habitable areas were only sparsely settled or had limited economies. Large areas exhibiting these characteristics are found along the western coasts of the American continents, in parts of north and south-east Africa, in many of the Caribbean and Atlantic islands, as well as in the Middle East and part of Australia.

(a) Desalination

Desalination is a separation process that treats saline water to reduce the dissolved salt content to a usable level. The use of desalination overcomes the paradox many coastal communities face of having lots of water (saline) but no way to use it. Although some substances dissolved in water, such as calcium carbonate, can be removed by straightforward chemical methods, other common constituents, like sodium chloride, require more technically sophisticated methods such as desalination. The difficulty and expense of removing various dissolved salts from water in the past made saline waters an impractical source of potable water. Early desalination methods employed variants of the distillation process with heat supplied by fossil fuels or solar energy. This type of desalination was known and used at various locations through the 19th and 20th centuries. However, it was not until the 1950s that desalination began to appear practical for ordinary use.

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By the year 1950, only a few widely scattered land-based desalination plants were in operation, with a total world-wide capacity of approximately 9,500 $m^3/d$ (2.5 mgd). During the 1950s, which was a decade of discovery for desalination, work began on developing various methods for desalination, including distillation, freezing, electrodialysis, and reverse osmosis.

(b) Development

The development of commercially viable desalination processes that began in the 1950s is continuing today. As shown in table 2, the four major processes achieved different levels of commercial acceptance and success. By 1960, an additional 115,000 $m^3/d$ (30 mgd), of desalination capacity was installed worldwide. In the next 10 years, this was increased by approximately 720,000 $m^3/d$ (190 mgd). By the beginning of 1984, the total installed desalination capacity was about 7.6 million $m^3/d$ (2 billion gpd). The majority of this capacity is in multiple-stage flash distillation units, most of which are installed as part of dual-purpose (power-water) generating stations in the Middle East and North Africa.

Aside from distillation, the other desalination processes that have become commercially viable are electrodialysis and reverse osmosis. Freezing, which in the 1950s seemed to be a viable process, has not attained commercial success. Membrane distillation, a fifth process for desalting saline water, is still under development and has a limited number of commercial installations.

(c) Available Processes

The three major desalination processes available are distillation, electrodialysis and reverse osmosis. Electrodialysis and reverse osmosis are used for desalting brackish water, while reverse osmosis and distillation are used to desalinate sea water.

Table 2. The capacity of desalination plants sold or installed during three 10-year periods from 1951 to 1980

| | Capacity in $m^3/d$ | | | Capacity in mgd | | |
|---|---|---|---|---|---|---|
| | 1951-1960 | 1961-1970 | 1971-1980 | 1951-1960 | 1961-1970 | 1971-1980 |
| Distillation | | | | | | |
| MSF | 27,600 | 506,100 | 2,700,000 | 7.1 | 133.5 | 713.0 |
| Other | 90,100 | 170,900 | 379,000 | 23.8 | 45.1 | 100.0 |
| Freezing | — | 400 | 400 | — | 0.1 | 0.1 |
| Electrodialysis | | | | | | |
| Standard | 300 | 37,300 | 102,000 | 0.1 | 9.8 | 26.9 |
| Reversal (EDR) | — | — | 139,000 | — | — | 36.8 |
| Reverse Osmosis | — | 8,600 | 1,042,000 | — | 2.3 | 274.9 |
| TOTALS | 117,100 | 723,300 | 4,362,400 | 31.0 | 190.8 | 1,151.7 |

Notes to table 2:

1. 1951-1970 data based on El-Ramly and Congdon, 1977.

2. 1971-1980 data based on El Ramly and Congdon, 1981.

3. This data does not include plants with capacities less than 95 $m^3/d$ (25,000 gpd).

4. Included in the 1981 El-Ramly and Congdon report but not in this table are plants projected to be built between 1981 and 1984. These amount to about 2,190,000 $m^3/d$ (580 mgd) of added capacity.

5. Table adapted from Buros, and others, 1984.

## 2. Distillation

The distillation process is a phase separation method where saline water is heated to accelerate the production of water vapour and the water vapour is condensed to produce fresh water. A number of configuratons are used to produce potable water, including the multiple-stage flash, multiple-effect, vapour compression, and waste-heat type of evaporators. All of these generally operate on a principle of reducing the vapour pressure within the unit to permit boiling to occur at various temperatures, without the continual addition of heat. They routinely use designs that conserve as much thermal energy as possible through interchanging the heat of condensation and heat of vaporization of the water within the units. The major energy requirement in the distillation process is in providing the heat of vaporization to the feed water.

Distillation is the oldest and most commonly-used method of desalination. Before the 1950s, these plants were generally made with heating tubes submerged in sea water. The heat applied inside the tubes boiled the sea water and the resulting vapour was condensed to produce fresh water. These units were not efficient by today's standards, but they worked and were installed in a number of areas in the Caribbean, Middle East and North Africa.

The commercial development of land-based sea-water distillation units took place in earnest in the late 1950s. This development initially relied in large part on technology developed with industrial evaporators (such as sugar concentrators) and with the shipboard distillers which were built during World War II. One of the key turning points came in 1957 with the patenting of the multistage flash (MSF) concept by Robert Silver of Glasgow, Scotland. The first two significant plants of this type were built in Kuwait and in the Channel Islands.

### (a) Multistage Flash (MSF)

The MSF plants became very popular and were an early leader in the field of desalination. In 1981, they made up over 65 per cent of the world's desalination capacity, with a total installed capacity of about 5 million $m^3/d$ (1,300 mgd).

Figure 1 shows a simplified flow sheet of a multistage flash unit. The incoming sea water first passes through the heat rejection stage(s) and then is heated in the heat recovery sections in each subsequent stage. After passing through the last heat recovery section and before entering the first stage for flashing, the feed water is further heated in the brine heater using externally supplied steam. This raises the feed water to its top temperature, after which it is passed through the various stages where flashing takes place. The vapour pressure in each of the stages is controlled so that the heated brine enters each chamber at the proper temperature and pressure combination (each lower than the preceeding stage) so that instantaneous and violent boiling occurs.

Various types of orifices and baffles are used between stages to produce this pressure drop, to promote surface area exposure (to maximize vapour production), and to prevent brine droplets from being passed into the condensed fresh water. In each stage the vapour passes through demisters and is condensed to form fresh water in the heat recovery section of the plant on the outside of tubes carrying the saline feed water to the brine heater at the head of the plant. The cooler feed water is heated by the transfer of the heat of condensation created when the vapour changes to a liquid.

The fresh water formed by condensation of the vapour is collected in each stage and is passed on from stage to stage in parallel with the brine. In each stage, the product is also flashed so that it can be cooled and the heat recovered for heating the feed water.

Due to the large amount of flashing brine required in an MSF plant, a portion (50-75 per cent) of the brine from the last stage is often mixed with incoming feed water and recirculated through the heat recovery sections to the brine heater and is then flashed again through all the stages. A facility of this type is often referred to as a "brine recycle" plant. This mode of operation reduces the amount of water-conditioning chemicals that must be added; this can significantly affect operation costs. On the other hand, it increases the salinity of the brine at the hot end of the plant, thereby increasing the boiling point rise and increasing the danger of corrosion and scaling in the plant. A plant which does not recirculate a portion of the brine is referred to as a "once-through" plant.

The advantages of MSF plants lie in their ability to be constructed in large capacities, the fact that boiling does not take place on a hot tube surface (it flashes instead), the considerable design and operational experience accumulated over the past 25 years, and the widespread manufacture of the units through the world.

Its disadvantages involve the potential for scaling and corrosion, the potential difficulties involved in start-up, the inability to operate the plant below 70-80 per cent of design capacity, the sensitivity of product water to salt contamination by pinpoint leaks in the heat recovery (condensing) tubes, and the necessity for pumping, treating, and heating large quantities of salt water relative to the product.

MSF plants have been extensively used in the Middle East, North Africa and the Caribbean.

(b) Other distillation processes

Two other distillation processes of importance for potable water production are multiple-effect and vapour compression.

In multiple effect units steam is condensed on one side of a tube wall while saline water is evaporated on the other side of the tube wall (see figure 2). The energy used for evaporation is the heat of condensation of the condensing steam. Usually there is a series of condensation-evaporation processes taking place (each being an "effect"). The saline water is usually applied to the tubes in the form of a thin-film so that it will evaporate easily. Although this is an older technology than the MSF process, having been used in sugar refineries, it has not been extensively utilized for water production. However, lately a new type of low-temperature horizontal-tube, multiple-effect process has been successfully used in the Caribbean. These plants appear to be very rugged, easy to operate and yet economical since they can be made out of aluminium and other low-cost materials.

The vapour compression process uses mechanical energy rather than direct heat as a source of thermal energy. Vapour is drawn from the evaporation chamber by a compressor and then the pressurized vapour (emerging from the compressor) is condensed on the opposite side of tubes located in the same chamber. The heat of condensation is used to evaporate a film of saline water applied to the other side of the tubes inside the evaporation chamber. These units are usually built in capacities less than 100 $m^3/d$ (25,000 gpd) and are often used at resorts and industrial sites.

(c) Dual-purpose plants

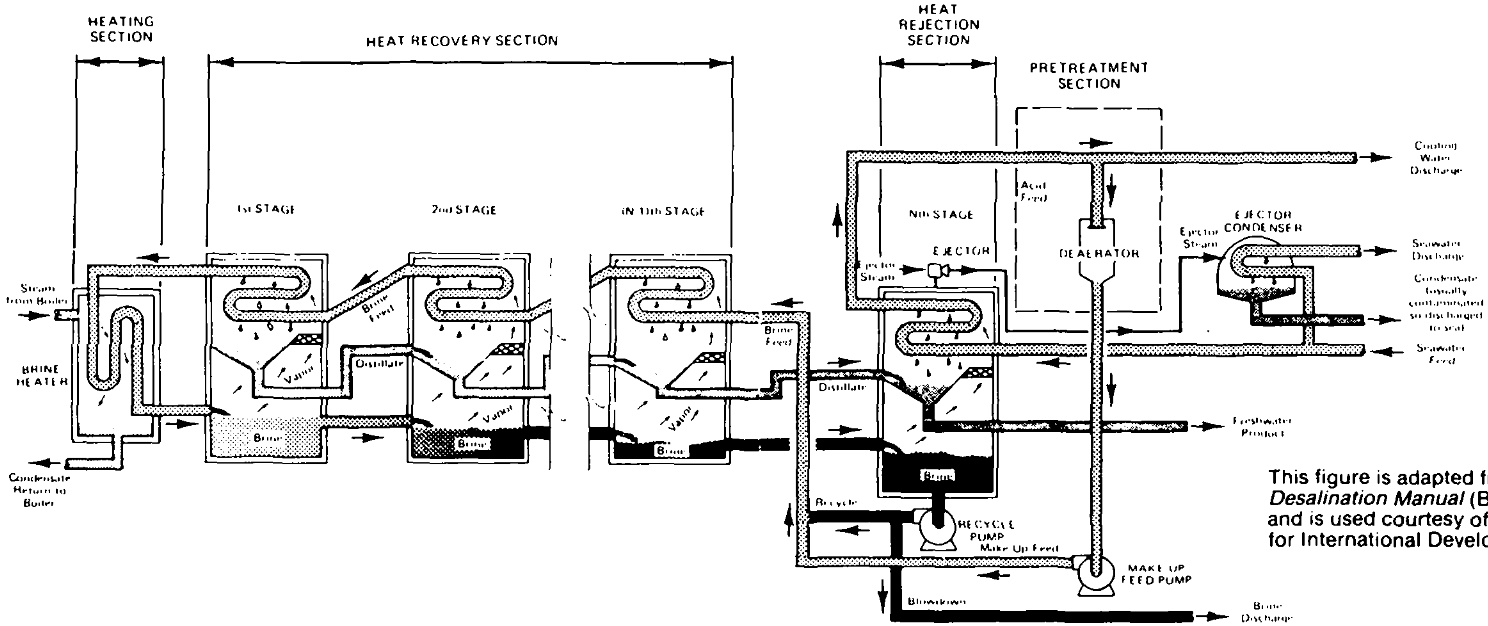
Most of the large distillation units in the world are dual-purpose facilities. Specifically, they derive their source of thermal energy from the steam that has passed through a turbine that powers an electric generator. Thus, water is heated in a boiler to a high-energy level and is passed through a turbine (to produce rotating energy to turn a generator); the steam is then extracted from the turbine to be used at a lower temperature to provide the heat in the distillation plants.

The advantage of this arrangement is that it substantially reduces the amount of energy necessary to run the two units compared to the amount required if both had independent heat sources.

The disadvantage is that the two plants become interdependent. If the electric plant or its boiler does not run, the distillation plant likewise cannot run.

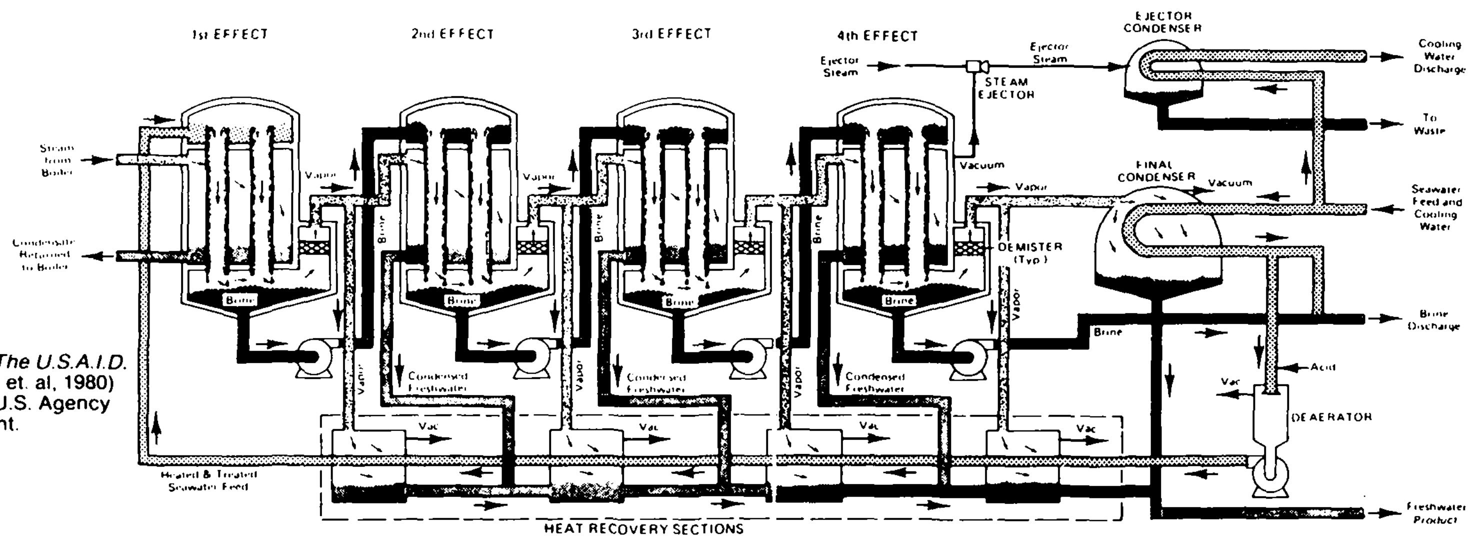
## 3. Electrodialysis

Electrodialysis is a membrane separation process. It was commercially developed in the mid-1950s at least a decade before reverse osmosis. The development of electrodialysis in the United States gave a major impetus for the United States Congress to fund research on desalination through the establishment of the Office of Saline Water.




This figure is adapted from *The U.S.A.I.D. Desalination Manual* (Buros, et. al, 1980) and is used courtesy of the U.S. Agency for International Development.

Figure 1. Simplified flow diagram of a Multistage Flash (MSF) distillation plant




This figure is adapted from *The U.S.A.I.D. Desalination Manual* (Buros, et. al, 1980) and is used courtesy of the U.S. Agency for International Development.

Figure 2. Simplified flow diagram of a Vertical-tube Multiple-effect distillation plant

Electrodialysis depends on the observed conditions that (1) most salts dissolved in water are ionic in nature (cations or anions), (2) these ions are attracted to electrodes with an opposite electrical charge, and (3) membranes can be constructed to permit selective passage of these ions.

To utilize this phenomenon to desalinate water, membranes which will allow either cations or anions (but not both) to pass are placed between the electrodes (see figure 3). These membranes are arranged alternately with an anion-selective membrane followed by a cation-selective membrane. In between each membrane a spacer sheet is placed which permits water to flow along the face of the membrane. One spacer carries feed (and product) water and the other carries brine. As the electrodes are charged, the anions are diverted from the main product stream (making it dilute) toward the positive electrode and pass through the anion-selective membrane into a concentrate (or brine) cell. The anions are prevented from continuing on through the adjacent cell wall, as it is a cation-selective membrane and prevents their passage. Similarly, cations under the influence of the negative electrode move from the main product stream on the other side of the cation-selective membrane into the concentrate cell. Here they are prevented from moving further toward the negative electrode by the anion-selective membrane. By this arrangement, concentrated and dilute solutions are formed in the spaces between alternating membranes. These spaces, bound by two membranes (one anionic, the other cationic), are called "cells." A cell pair consists of two cells, one from which the ions migrated (dilute cell for the product water) and the other in which the ions concentrate (concentrate cell for the brine stream).

A typical network (or membrane stack) has several hundred cell pairs (one dilute and one concentrate cell) so that the proportion of ions removed from the feed stream relative to the current carried by the ions between the electrodes is very large. In operaton, feed water passes simultaneously in parallel paths through all of the cells to provide a continuous flow of product water and brine stream, thus washing out the concentrated ions.

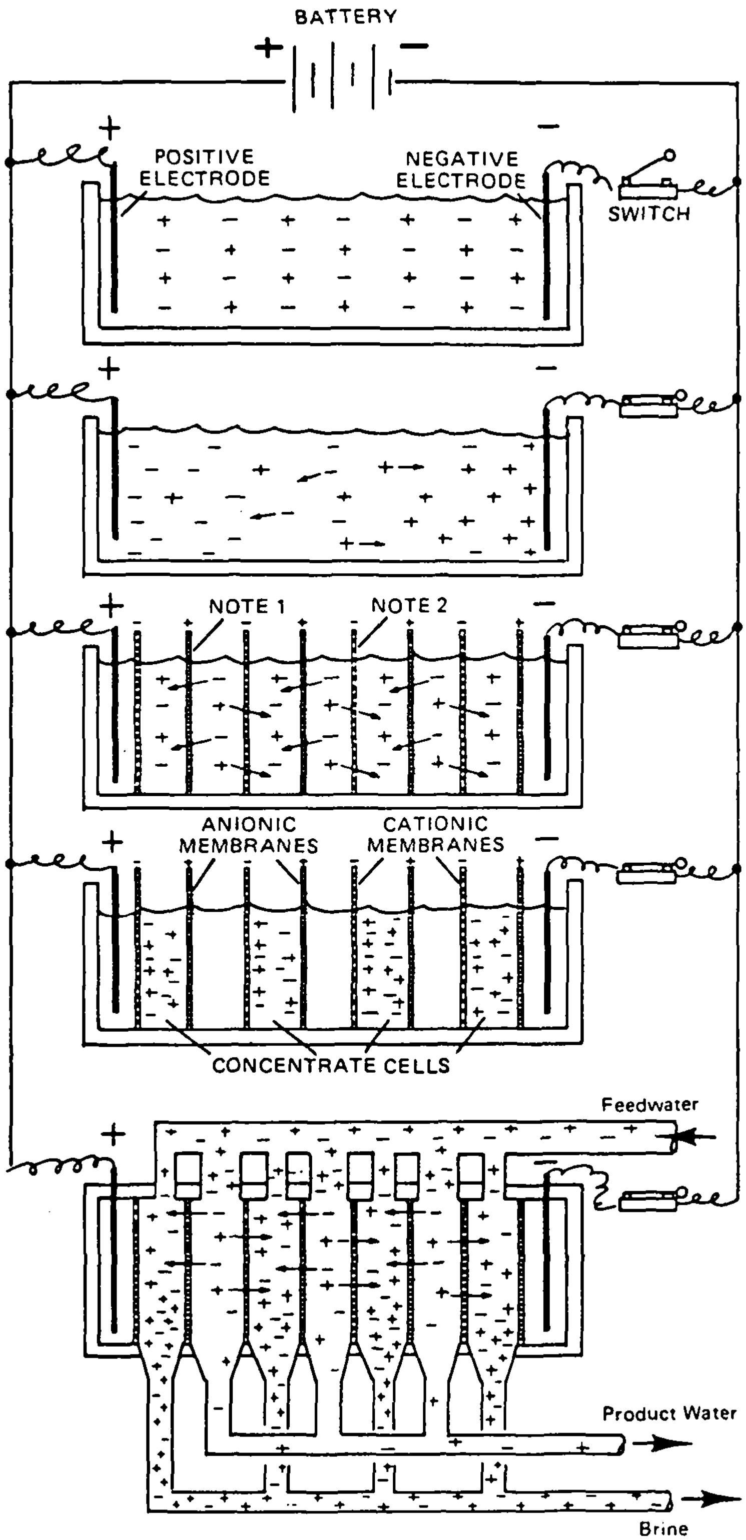
The dissolved ionic constituents in a saline solution are dispersed in the water, effectively neutralizing their individual charges. When electrodes, connected to an outside source of direct current, are placed in a container of saline water, the current is carried through the solution (a mild electrolyte due to the ionized salts), and the ions tend to migrate to the electrodes which carry the opposite charge. Thus anions, such as chloride ($Cl^-$), migrate toward the positive electrode, and cations, such as sodium ($Na^+$) migrate toward the negative electrode.

(a) <u>Elements of an electrodialysis unit</u>

An electrodialysis unit is made up of the following basic components:

DC Power Supply (Rectifier)
Membrane Stack
Low Pressure Circulation Pump and Hardware
Pretreatment

These are shown diagrammatically in figure 4.




Many of the substances which make up the total dissolved solids in brackish water are strong electrolytes. When dissolved in water they ionize; that is, the compounds dissociate into ions which carry an electric charge. Typical of the ions in brackish water are $Cl^{-1}$, $Na^{+1}$, $HCO_3^{-1}$, $Mg^{+2}$, $SO_4^{-2}$, and $Ca^{+2}$. These ions tend to attract the dipolar water molecules and to be diffused in time, fairly evenly throughout a solution.

If two electrodes are placed in a solution of ions, and energized by a battery or other direct current source, the current is carried through the solution by the charged particles and the ions tend to migrate to the electrode of the opposite charge.

If alternately fixed charged membranes (which are selectively permeable to ions of the opposite charge) are placed in the path of the migrating ions, the ions will be trapped between the alternate cells formed.

Note 1: A positively fixed charge (anionic) membrane will allow negative ions to pass, but will repel positive ions.

Note 2: A negatively fixed charge (cationic) membrane will allow positive ions to pass, but will repel negative ions.

If this continued, almost all the ions would become trapped in the alternate cells (concentrate cells). The other cells, which lack ions, would have a lower level of dissolved constituents and would have a high resistance to current flow.

The phenomenon illustrated above is used in electrodialysis to remove ions from incoming saline water on a continuous basis. Feedwater enters both the concentrate and product cells. Up to about half of the ions in the product cells migrate and are trapped in the concentrate cells. Two streams emerge from the device: one of concentrated brine and the other with a much lower concentration of TDS (product water).

**This figure is adapted from *The U.S.A.I.D. Desalination Manual* (Buros, et. al, 1980) and is used courtesy of the U.S. Agency for International Development.**

Figure 3. Principles of operation of an electrodialysis unit

(b) Electrodialysis reversal process (EDR)

In about 1972 the Ionics Company introduced the EDR process. The reversal process operates on the same basic principles as the standard electrodialysis unit, except that both the product and the brine cells are identical in construction. At intervals of three to four times per hour, the polarity of the electrodes is reversed and the flows are simultaneously switched by automatic valves in the stacks so that the product cell becomes the brine cell and the brine cell becomes the product cell. The salts are thus transferred in opposite directions across the membranes.

Following the reversal of polarity and flow, the product water is discharged until the cells and lines are flushed out and the desired water quality is achieved. This takes approximately one to two minutes. During this short period, the product water is dumped and then the unit starts to produce water which can be utilized. The reversal process aids in breaking up and flushing out scale, slimes, and other deposits in the cells. Its main advantage is that it drastically reduces the use of pretreatment chemicals and minimizes fouling of the membranes.

(c) Application

Electrodialysis units are normally used to desalinate brackish water and the energy used is generally proportional to the salt concentration in the water being treated. The major power requirement is used to produce the electrical charge applied to the electrodes.

## 4. Reverse Osmosis

In comparison to distillation and electrodialysis, reverse osmosis is relatively new, with successful commercialization only occurring in about 1970.

Reverse osmosis is a membrane separation process in which the water from a pressurized saline solution is separated from the solutes by flowing through an appropriate membrane. The permeate (the liquid flowing through the membrane), which emerges near atmospheric pressure, is reduced in salt content while the feed solution, which is pressurized on the other side of the membrane, concomitantly increases in salt content. As no heating or phase change takes place, the major energy usage in the process is that required to pressurize the feed. For brackish water desalination the operating pressure ranges from 17 to 27 atm (250 to 400 psi), and for sea water desalination it averages from 53 to 67 atm (800 to 1,000 psi).

The reverse osmosis process operates with three major streams. These are listed below:

| Stream | Salt Content | Pressure |
|---|---|---|
| Saline feed water | High | High |
| Brine | Higher | High |
| Product (Fresh water) | Low | Low |

In the actual process, saline water is pumped to pressurize it against a membrane in a closed container. Figure 5 illustrates the basic components of a reverse osmosis system. As pure water from the feed solution passes through the membrane, the remaining solution becomes more and more concentrated. At the same time, an orifice at point A allows a portion of this concentrated feed water to be discharged without passing through the membrane. Without this discharge, the concentration of dissolved salts in the feed solution would continually increase, requiring the pump to add ever-increasing energy to overcome the increased natural osmotic pressure. In addition, precipitation of supersaturated constituents in the concentrated feed water (brine), and other complicatons, would occur.

(d) Elements of a reverse osmosis system

A reverse osmosis system consists of four major components/processes: (1) pretreatment, (2)high-pressure pump, (3) membrane assembly, and (4) post-treatment for stabilization.

Pretreatment. The incoming feed water is treated so that it is compatible for use with, and protection of, the membranes. This treatment usually consists of the removal of suspended solids, the adjustment of pH, and the addition of a threshold inhibitor for controlling scaling due to constituents such as calcium sulphate.

High-Pressure Pump. The pump energizes the pretreated feed water to the pressure appropriate for the membrane and feed water being used.

Membrane Assembly. The semi-permeable membranes inhibit the passage of dissolved salts while permitting almost salt-free water to pass through. Feed water applied to the membrane assembly results in a fresh water product stream and a concentrated brine reject stream. No membrane is perfect in its rejection of dissolved salts, so a small percentage of salts does move through the membrane and appears in the product.

Reverse osmosis membranes come in a variety of configurations. Two of the most popular are spiral wound and hollow fine fibre membranes. Both of these are used for brackish water and sea water desalination, although the specific membrane and the construction of the pressure vessel to contain them vary due to the wide differences in operating pressures. They are illustrated in figures 6 and 7.

Stabilization. The product water from the membrane assembly usually requires pH adjustment and/or degassification before being transferred to the distribution system for potable use.

(b) General

The most significant costs associated with reverse osmosis, aside from capital cost, are the costs for electricity, membrane replacement and labour. The electricity is used mainly to drive the pumps to produce the high

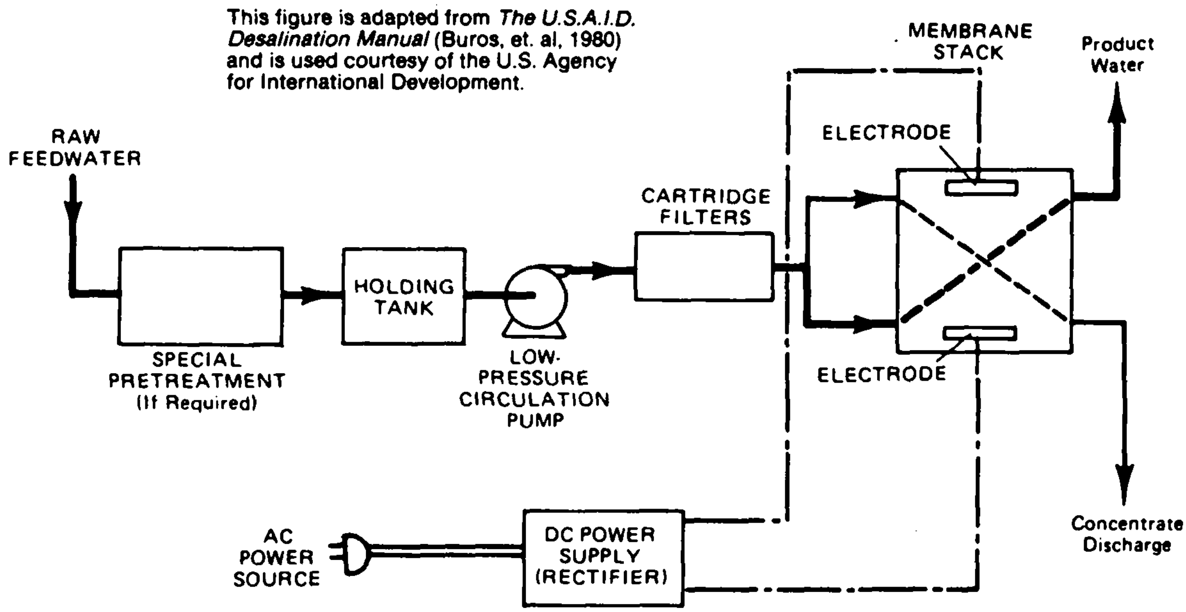



Figure 4. Major components and flow diagram of an electrodialysis unit

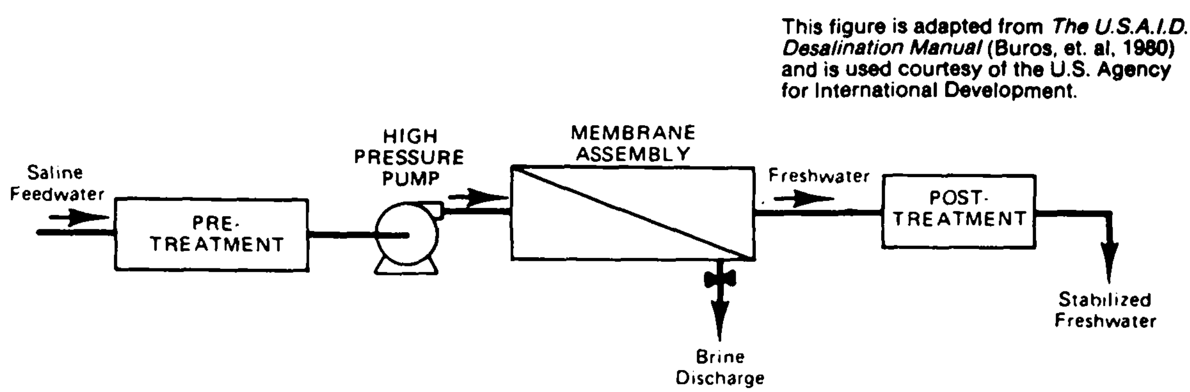
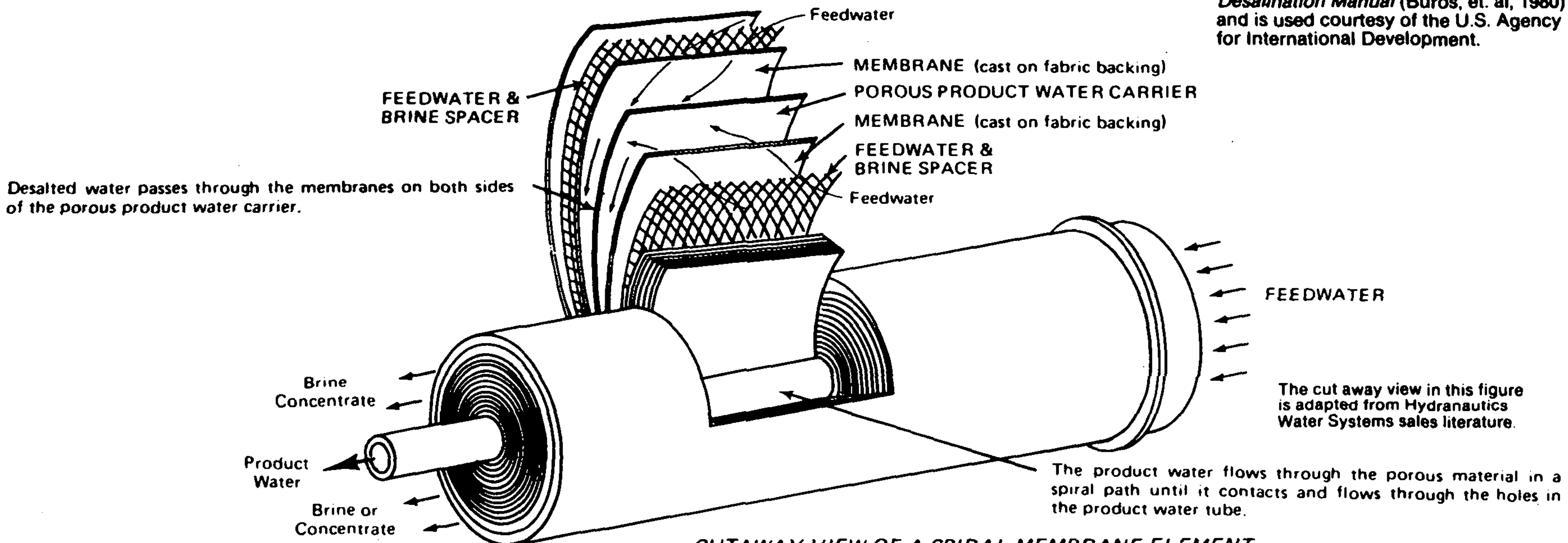


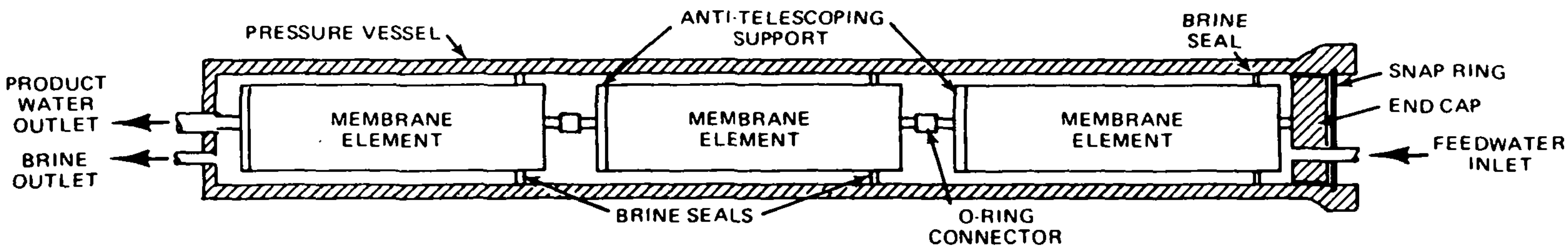

Figure 5. Major components and flow diagram of a reverse osmosis unit

This figure is adapted from *The U.S.A.I.D. Desalination Manual* (Buros, et. al, 1980) and is used courtesy of the U.S. Agency for International Development.




The cut away view in this figure is adapted from Hydranautics Water Systems sales literature.

CUTAWAY VIEW OF A SPIRAL MEMBRANE ELEMENT




CROSS SECTION OF PRESSURE VESSEL WITH 3-MEMBRANE ELEMENT

Figure 6. Basic components of a spiral wound reverse osmosis membrane

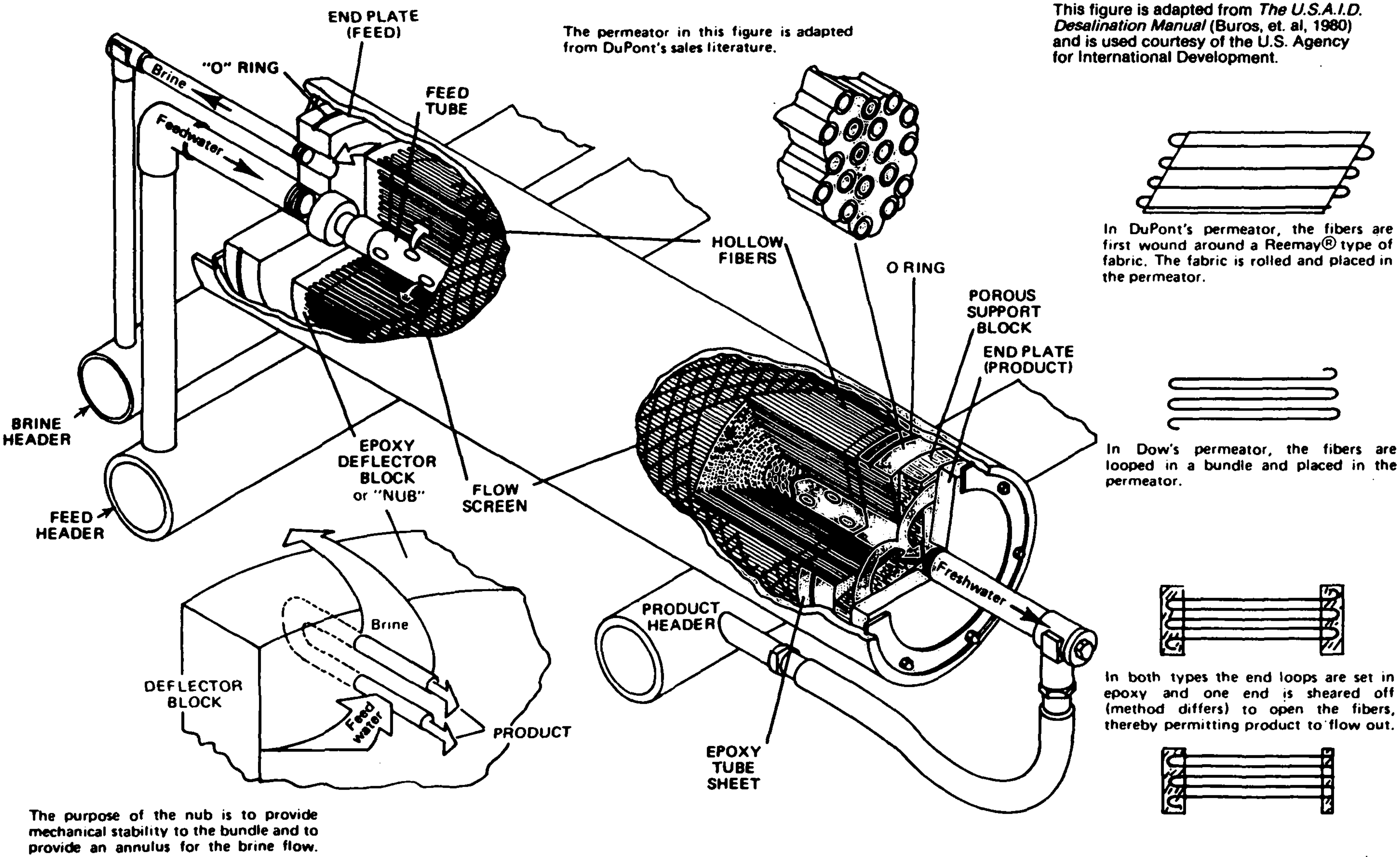



Figure 7. Basic components of a hollow fine fibre reverse osmosis membrane

pressures necessary. For brackish water this amounts to about 2 to 3 $kWh/m^3$ of product water (8 to 12 kWh/1,000 gal) and for sea water this could be on the order of 8 to 10 $kWh/m^3$ (30 to 40 kWh/kgal). With energy recovery units, the energy requirements on sea water plants can be significantly cut. The membranes last from three to five years and then need replacement. Aside from that, operation requires labour, some chemicals, and filters. With care, the units can operate well; otherwise they, like other desalination units, can have problems.

## 5. Other processes

Two other desalination processes of interest are freezing and membrane distillation.

### (a) Freezing

Extensive work was undertaken in the 1950s and 1960s to develop freezing desalination. The freezing process works due to the natural phenomenon that during freezing dissolved constituents, like salts, are naturally excluded in the formation of the ice crystals. To desalinate sea water the sea water is cooled and the crystals are formed under controlled conditions. Then the ice is washed to remove any salts or brine which has adhered to the crystals.

Theoretically, freezing has considerable advantages over distillation which was the predominant process during the 1950s and 1960s. These advantages include a considerably lower energy requirement, minimal corrosion potential, and little scaling or precipitation. Unfortunately, the process which involves the handling of both solids and liquids was too complicated and has never been a commercial success.

There are only a few small experimental plants in existence at present. The most interesting one is an indirect freezing unit being built as part of a solar-powered desalination facility in Saudi Arabia.

### (b) Membrane distillation

Membrane distillation, on the other hand, is a relatively new process being introduced commercially in only the last few years. The process works by the use of a special membrane which has the characteristic that it will pass water vapour but not liquid. The membrane is placed over a moving stream of warm water and, as water vapour passes through the membrane, it is condensed by a second surface which is at a lower temperature than the feed water.

Thus far the process has been used in only a few areas and a small number of membrane configurations and commercial units have been built. Its current applications are almost entirely restricted to North America and the Caribbean but if the reliability is proven in commercial use it can be expected to expand in usage. Its chief advantage is its simplicity and need for only small temperature differentials to operate.

## 6. Applications

There are numerous areas in the world where society could benefit from the production of fresh water from saline water sources. Unfortunately, the economics involved do not always permit the use of desalination techniques.

All of the desalination techniques are energy-intensive relative to what are generally considered standard water treatment practices. This is especially true of sea water desalting. General costs for a 19,000 $m^3/d$ (5 mgd) desalinaton plant have been estimated as follows:

| | Capital Cost Per Unit of Daily Capacity | | Operation & Maintenance Per Unit of Production | |
|---|---|---|---|---|
| | ($/gpd) | ($/$m^3$/d) | ($/1,000 gal) | ($/$m^3$) |
| Brackish Water | $1.44 to 2.13 | $380 to 562 | $1.05 to 1.57 | $0.28 to 0.41 |
| Sea Water | $5.08 to 9.01 | $1341 to 2379 | $3.90 to 5.82 | $1.02 to 1.54 |

These cost estimates were cited in a recent US Army Corps of Engineers study (DSS and Missimer, 1984) and are for reasonably accessible sites in Florida. The estimates that were made for sea water desalination included both the distillation and reverse osmosis processes. The distillation costs were for single purpose plants and thus tended to be high. The lowest cost was for a reverse osmosis plant using the optimum low cost alternative which was a unit that had a sea well to minimize pretreatment and energy recovery to reduce energy costs. For the brackish water units the lowest cost was obtained by considering the use of low pressure membranes which were introduced into the industry in 1983 and assuming that there would be no problem with brine disposal. Although the lowest costs for both brackish and sea water desalination are based on rather idealized conditions, the overall cost range given is probably appropriate for cost estimation purposes. The actual costs will be very dependent on site-specific conditions.

The major costs of production for all of the processes are energy, labour and amortization of capital costs. With the reverse osmosis and electrodialysis processes membrane, replacement costs are also significant. Chemicals, filters, routine maintenance, etc., also add to the costs.

Cost estimates for any proposed desalination facility must be reviewed carefully as they are very dependent on the assumptions made relative to such items as site work, interest rates, energy costs, labour required, estimated plant life, repairs needed, brine disposal, etc. Two factors which have occasionally been poorly estimated in the past (especially for prototype units) have been plant life (over-estimated) and the cost of major repairs or overhauls (under-estimated).

In some areas of the world these costs exceed the monies available for water, and desalination cannot be economically used. Currently, desalination capacity is geographically distributed in approximately the following manner:

| Area | Percentage |
|---|---|
| Middle East | 58 |
| North America | 17 |
| Africa | 8 |
| Europe | 7 |
| Asia and Pacific | 5 |
| USSR | 3 |
| South America | 2 |

These data, by El Ramly and Congdon (1981), demonstrate the concentration of desalination capacity in the arid Middle East and North African areas, where both the need and the monies exist to finance the use of desalination. This use is primarily for potable or selected industrial purposes and not for agriculture irrigation, where very low-cost water is required.

Where desalination facilities are installed on small water-short islands such as exist in areas of the Caribbean and Pacific, they are often being used at petroleum refineries, hotels, resorts, etc., which can afford to use a high-cost water supply.

Most of the desalination facilities in the United States are used to treat brackish water in areas where new developments are being built in places such as Florida's south-west coast. These areas are generally residential only and can support the costs associated with desalination.

## Summary

Desalination technology has been extensively developed over the past three decades to a point where it can be reliably used in many areas to produce fresh water from saline sources. This innovative process is another tool which enables man to meet his water needs through proper water resource development.

There is no one "best" method of desalination. Generally, distillation and reverse osmosis are used for sea-water desalting while reverse osmosis and electrodialysis are used for brackish-water desalination. However, the selection of these processes should be dependent on site conditions, and the proper application must be selected very carefully. Circumstances can arise which would alter the selection in order to provide the most cost-effective method for a particular area.

The best selection of a desalination system is one which is more than economically reasonable in the paper study stage. It is a system which works when it is installed and continues to work and deliver a product at the expected quantity, quality, and cost for the planned life of the project.

Acknowledgements

Several other publications written by this author were used to produce some of the material in this paper. These publications were: The USAID Desalination Manual (Buros, and others, 1980); the Water Management Plan for the Public Water System, U.S. Virgin Islands, (Buros, 1983); "An Overview and Brief Description of Desalination Processes" (Buros, 1984); and "Progress in Desalination Technology" (Buros, and others, 1984). Figures 1 through 7 are adapted from The USAID Desalination Manual, courtesy of the United States Agency for International Development.

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## B. Recent developments in vapour compression desalination

by Marc Lucas*

When sea water distillation is discussed, it usually refers to the conventional multi-stage flash (MSF) process. This is of course justified in the case of large-size units combined with a power plant as, for example, the 267,000 $m^3$/day facility in Al Khobar, Saudi Arabia, but other processes can be more appropriate in cases where smaller size units are needed. One of these other processes is the multi-effect vapour-compression process working at low temperature (around 60°C) with a spray-film evaporator.

Some reasons to use this process would be:

1. Distillation is currently the only process with proven industrial experience. Furthermore, it avoids regular and costly replacements of the equipment (such as the membranes of reverse osmosis). Up to now, 95 per cent of sea water desalination worldwide is performed by distillation.

2. The multi-effect process saves energy. For given conditions of production and energy available, an optimization has to be found between the number of cells and the thermal exchange surface.

3. The spray-film and cross-tube evaporator improve the thermal exchange coefficient. This means lower investment costs and low energy consumption.

4. The low temperature process using an upper limit of 60°C has been chosen to avoid problems of scaling and corrosion. No particular pre-treatment of the sea water is required. This means longer life of the units and easier and cheaper operation and maintenance.

5. The compactness of the skid-mounted units means lower investments, transportation and erection costs.

If part of the vapour produced is recompressed in the vapour compression unit, the compression can be performed either by a thermal ejector or by a mechanical compressor. A full range of standard skid-mounted package units for all capacities from 10 tons/day to 2,000 tons/day both with ejecto-compression or mechanical compression have been developed.

Some examples of these units in the Caribbean are:

1. Mechanical compression: 90 tons/day, 200 tons/day and 700 tons/day in St. Maarten and Guadeloupe.

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2. Ejecto-compression: 168 tons/days as a mobile unit in Mexico and 450 tons/day with heat recovery from diesel engines in St. Maarten.

3. Multi-effect: 2 x 4,540 tons/day in Antigua (constructed by Ishikawajimi Heavy Industries Co., Ltd. with SIDEM's engineering and design).

The water cost is dependent on a number of factors. Tables 3, 4 and 5 consider the cost of one unit producing 1,500 $m^3$/day using multi-stage flash, ejecto compression or mechanical compression. The figures given in the following three tables, using a case from the Caribbean area, must be adapted to the specific conditions of each site.

Figure 8 shows a simplified flow diagram of the ejecto-compression process. Sea water is fed to the last cell in which it flows through condenser C, which carries off the heat brought by the boiler. On leaving the last cell, a certain amount of the sea water is rejected. The remainder A, called "sea-water make-up" is sprayed over the heating bundles F.

In the first cell, part of the sea water is vaporized and the difference (now called brine), flows into the bottom of cell number 2. The vapour produced in cell number 1 flows into the tubes of heating bundle F2 in which it is condensed. When condensing in the heating bundle F2, this vapour gives up sufficient heat to vaporize an equivalent quantity of sea water being sprayed over the bundle. In evaporators having more than 2 cells (3, 4, 5 or up to 8), the process repeats itself in all the following cells. In the last cell, part of the vapour produced is condensed over condenser bundle C, leaving part of its heat, thus heating up the sea water that flows through the condenser.

The remaining vapour is sucked and compressed by an ejecto-compressor using the steam Qm supplied by a boiler or an external source as motive steam. On leaving the ejecto-compressor the mixed motive steam and vapour is delivered into the heating bundle F1 in which it is condensed by transmitting a sufficient amount of heat to evaporate the sea water, as stated above. In order to prevent too high a concentration of dissolved salts in the evaporation chambers, the quantity of "make-up" sea water is greater than the distillate producton. Excess brine is drained from the bottom of the last cell. Working at low temperature, the unit includes a vacuum system which maintains a low pressure by extracting air due to leaks and dissolved gasses in the make-up sea water. It consists of either a steam ejector or a water-ejector.

In the case of mechanical compression, the ejector is replaced by a centrifugal compressor, and plate heat exchangers are installed on both brine reject and distillate production lines in order to heat up the sea water. This allows it to reach a very low energy consumption (down to 10 kwh/m3).

In conclusion, these mechanical and vapour compression units are often appropriate to developing countries because they combine the well-known advantages of distillation with easier and cheaper operation and maintenance.

Table 3. Tentative cost of water for an MSF unit
(US dollars per $m^3$)

| | |
|---|---|
| Type of unit | MSF 1500 (GOR 10) |
| Process | MSF |
| Daily Capacity | 1,500 $m^3$ |

**Direct investment cost in US dollars**

| | |
|---|---|
| FOB price (with associated boiler) | 2,000,000 |
| Shipment and local transport | 200,000 |
| Civil works and seawater intake | 300,000 |
| Erection and commissioning | 300,000 |
| Total (1) | 2,800,000 |

| | |
|---|---|
| Total operating days per year | 330 |
| Total plant output per year in $m^3$ | 500,000 |
| Power consumption (6 $kWh/m^3$) in kWh | 3,000,000 |
| Heat Consumption in Kg of fuel at 10,000 kCal/Kg (8.2 $kg/m^3$) | $4{,}100 \times 10^3$ |

**Annual operating costs in US dollars**

| | |
|---|---|
| Operation and maintenance | 150,000 |
| Overheads and administrative expenses (40% of O and M) | 60,000 |
| Spares | 40,000 |
| Chemicals | 30,000 |
| Energy: Electricity ($0.10/kWh) | 300,000 |
| Fuel ($270/ton) | 1,107,000 |
| Total (2) | 1,687,000 |

**Annual fixed charges**

| | |
|---|---|
| Amortization over 15 years at 15 % interest | |
| Total (3) | 479,000 |
| Total annual cost (2) + (3) | 2,166,000 |
| Cost of water in US dollars per $m^3$ | 4.33 |

Table 4. Tentative cost of water for an ejecto compression unit (US dollars per $m^3$)

| | |
|---|---|
| Type of unit | 4 T 1500 (model) |
| Process | Ejecto compression |
| Daily Capacity | 1,500 $m^3$ |
| **Direct investment cost in US dollars** | |
| FOB price (with associated boiler) | 1,450,000 |
| Shipment and local transport | 150,000 |
| Civil works and sea-water intake | 250,000 |
| Erection and commissioning | 150,000 |
| Total (1) | 2,000,000 |
| Total operating days per year | 330 |
| Total plant output per year in $m^3$ | 500,000 |
| Power consumption (3 kWh/$m^3$) in kWh | 1,500,000 |
| Heat Consumption in Kg of fuel at 10,000 kCal/Kg (10 kg/$m^3$ | 5,000 x $10^3$ |
| **Annual operating costs in US dollars** | |
| Operation and maintenance | 100,000 |
| Overheads and administrative expenses (40% of O and M) | 40,000 |
| Spares | 25,000 |
| Chemicals | 20,000 |
| Energy: Electricity ($0.10/kWh) | 150,000 |
| Fuel ($270/ton) | 1,350,000 |
| Total (2) | 1,685,000 |
| **Annual fixed charges** | 360,000 |
| Amortization over 15 years at 15 % interest | |
| Total (3) | 288,000 |
| Total annual cost (2) + (3) | 1,973,000 |
| Cost of water in US dollars per $m^3$ | 3.95 |

Table 5. Tentative cost of water for a mechanical vapour compression unit
(US dollars per m3)

| | |
|---|---|
| Type of unit | 4 C 1500 |
| Process | Mechanical Vapour Compression |
| Daily Capacity | 1,500 $m^3$ |

| | | |
|---|---|---|
| **Direct investment cost in US dollars** | | |
| FOB price | | 1,900,000 |
| Shipment and local transport | | 140,000 |
| Civil works and seawater intake | | 200,000 |
| Erection and commissioning | | 120,000 |
| | Total (1) | 2,360,000 |
| Total operating days per year | | 330 |
| Total plant output per year in $m^3$ | | 500,000 |
| Power consumption (11 $kWh/m^3$) in kWh | | 5,500,000 |
| Heat Consumption | | none |
| **Annual operating costs in US dollars** | | |
| Operation and maintenance | | 100,000 |
| Overheads and administrative expenses (40% of O and M) | | 40,000 |
| Spares | | 25,000 |
| Chemicals | | 8,000 |
| Energy: Electricity ($0.10/kWh) | | 550,000 |
| Fuel | | none |
| | Total (2) | 723,000 |
| **Annual fixed charges** | | 424,800 |
| Amortization over 15 years at 15 % interest | | |
| | Total (3) | 403,600 |
| **Total annual cost (2) + (3)** | | 1,126,600 |
| **Cost of water in US dollars per $m^3$** | | 2.25 |

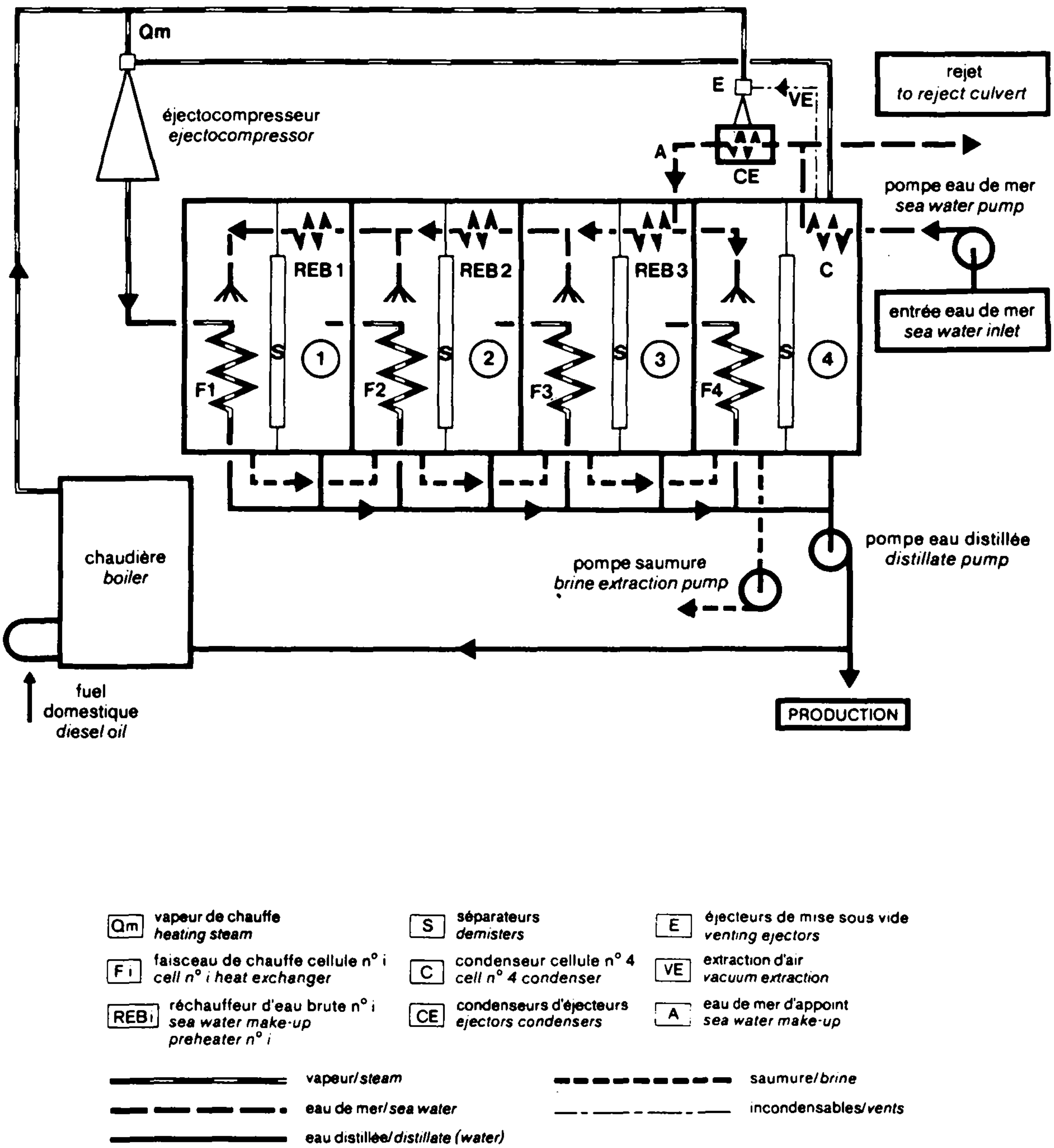


Figure 8. Flow diagram of an ejecto-compression desalination unit

## C. Recent developments in reverse osmosis

by Paul L. Culler*

The use of semi-permeable membranes for separating salt from water has come a long way since the late 1950s when serious research began. The early dream of desalting sea water utilizing reverse osmosis for $0.10 per 1000 gal. to make the deserts bloom, has not been realized. However, what has been realized is a maturing technology that is helping to solve water resource problems for potable uses, industry and agriculture. Over the past 15 years there has been a tremendous increase in the number and capacity of reverse osmosis plants in the world.

Twelve years ago researchers were struggling to separate out 90 per cent of the salt in feed water with total dissolved solids (TDS) levels of 1500 milligrams per liter (mg/l) using pressures of 600 pounds per square inch guage (psig) with a flux through the membrane of 12 - 13 gallons per square foot per day (gal/ft$^2$/day). Today typical brackish installations are being made which can separate, on a systems basis, 98 per cent of the salt from feed waters with TDS levels of 2500 - 3000 mg/l using pressures of 200 - 250 psig with a flux of 16 gal/ft$^2$/day, and guaranteeing to do it for 5 years without replacing the membrane.

The state-of-the-art today finds cellulose acetate and polyamide type membranes giving way to new thin film composite membranes. These new membranes work within a wider pH range, at higher temperatures and with broader chemical parameters, making them more rugged, able to withstand more operational abuse, and thus allowing their application to wider industrial use.

Desalting sea water with reverse osmosis has had its ups and downs since the first large scale installation was made in Jeddah, Saudi Arabia in the late 1970s. As a perfect membrane to desalt sea water is approached (i.e., 99 per cent salt rejection) only very minute imperfections in design and operation can be tolerated if World Health Organization (WHO) product water quality standards are to be maintained for an extended period of time. However, with the advent of thin film composite membranes, it appears that a milestone has been reached in building systems that will maintain their design quality for a period of three to five years without extensive membrane maintenance or replacement. Systems engineering is advancing with increased use of non-metallic components wherever possible to minimize the effects of corrosion in a very harsh environment.

Recovering energy from the system's reject stream receives continued attention as pelton wheels, reverse running pumps and other innovations are evaluated to reduce the net energy required to desalinate saline water. In addition, the latest state-of-the-art micro processors, data logging, and control are being applied where practical, to gain capital savings and better operation.

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In efforts to improve the efficient use of available water resources, it should be kept in mind that it is more economical to start with the lowest salinity water available, if there is a choice, upgrading the quality to satisfy the intended application. For example, polluted lake or river water is easier and more economical to treat than brackish water and brackish water is more economical to desalinate than sea water. This will generally be the case, at least with today's state-of-the-art technology. Applications utilizing reverse osmosis are being developed and refined for potable, industrial and agricultural uses.

## 1. Applications

### (a) Potable use

Until now we have always thought of reverse osmosis for its ability to desalt water. Since the "good" water is the water that passes through the membrane, a secondary benefit is its ability to serve as a "super filter". New membranes are under development that operate at 100 - 125 psig, and remove 60 - 75 per cent of the salt plus essentially all organics.

These membranes will, in the future, find wide acceptance for use on mildly brackish waters laden with organics, virus, bacteria and chemical pollutants. They will be used in place of coagulation-filtraton plants, which can be difficult to operate and control. A number of plants are in the feasibility and design phase with sizes from 5 to 20 million gallons per day (mgd). Also, this technology is readily adaptable to small packaged plants for use by small villages where the only source of water is a polluted river, lake, or water hole.

### (b) Industry

Industrial applications continue to flourish for the manufacture of electronic parts, boiler feed and chemical process applications. Extensive research continues in the food and pharmaceutical industry for use of reverse osmosis as a unit process tool where concentration and fractionation of a wet process stream is needed.

### (c) Agriculture

Agriculture through greenhouse and hydrophonic farming is beginning to use reverse osmosis in conjunction with controlled irrigation. Some developing countries have a number of installations using reverse osmosis to desalt and purify irrigation water in the growing of greenhouse vegetables, as salinity control is important for maximum plant growth. Also, since the membrane serves as a "super filter," the reverse osmosis product water tends to be low in bacteria and nematodes, which helps to control plant disease. The desalted/purified water is injected with the proper fertilizer constituents and fed directly to the plants, insuring proper quality and quantities of nutrients. An example of the use of reverse osmosis for this type of applicaton is a farmer in Florida with 22 acres within a greenhouse growing European cucumbers. The farm was using a canal water heavily laden with agricultural run-off water and produced about 4,000 dozen cucumbers per day.

They drilled a brackish well (the only ground water available), installed a 80,000 gallon per day (gpd) reverse osmosis system producing water with less than 15 mg/l of sodium. After the next planting their production increased to 7,000 dozen per day and over the term of the harvest, came close to doubling the yield per plant.

Reverse osmosis can play an important role in the production of vegetables for the developing countries if it is given the chance. Next to water for human needs, good water for growing table food and improving the quality of life for the people of the developing countries is second in importance.

## 2. Operating Experience

Operating experience with reverse osmosis technology has definitely improved over the past 15 years of commercial use. Fewer plants have long-term operational problems. Operational success or failure can be attributed to one or all of five areas: design, materials, construction, operation and maintenance. In the early days with the first installations, a lot was learned from mistakes in design and material selection. As time has passed fewer problems have arisen due to design, materials and construction, provided competent engineers and suppliers were selected. On some installations the selection process, through competitive bidding, has created downstream operational problems, due to the system supplier taking short cuts to minimize his costs to make up for a bad (too low) bid. It is the responsibility of the design engineer to ensure that a well designed system is installed. This is through his ability to write good specifications and prequalify potential suppliers as well as a willingness for the purchaser to pay a fair price for goods and services proposed.

Assuming that a properly designed and constructed unit was obtained, the success of the installation will depend on day-to-day monitoring of the system and the preventive maintenance performed on it. Preventive maintenance is extremely important. It is impossible to overstress the need for this. The need for instrument calibration, pump adjustments, chemical feeder inspection, leak repair, and just plain cleaning and painting the unit on a planned schedule, will save a lot of problems.

Monitoring the system combined with data collection on a daily basis, no matter what size the plant, has to be done. Many manufacturers will not honour the system warrantees and guarantees if tabulated data are not sent to them on a regular basis.

Operation, maintenance and monitoring are not possible if people are not properly trained to do the job. Careful selection of the individual to operate the system is as important as the selection of the design engineer and the system supplier. Poor operation and maintenance can and will destroy the best installation no matter what the size may be. A clear understanding of the supplied "operational handbook" is mandatory. The operator must be able to evaluate the system so as to know what to do when data indicate the membrane is potentially deteriorating and needs cleaning or other attention. Membrane fouling can be corrected, but membrane plugging usually results in membrane replacement, causing premature added expense.

## 3. Advantages

### (a) Simplicity

All that is needed for a system is an appropriate membrane housed in a suitable pressure vessel which is attached to a pump that will produce the required pressure with an adjustable valve to impose a back pressure on the membrane. The gauges, controls and valves are used to operate and monitor the system. The only complicating factor is finding or producing a clean supply of feed water to minimize the need for frequent cleanings of the membrane.

### (b) Packaging

The technology lends itself to pre-packaging assembled systems from a few gallons per day to 200,000 gpd for brackish water and up to 100,000 gpd for sea water. This pre-packaging allows for high mobility, even simple installation on trailers, trucks and barges.

### (c) Installation

Reverse osmosis systems can have a low cost of installation as compared to other methods. Data reveal costs of 15 per cent of total capital for mechanical and electrical installation, much below most thermal processes. This has value in developing countries when a larger percentage of total costs can be controlled at the factory.

### (d) Space

The systems have a very high space/capacity ratio: in the area of 200-500 gpd/$ft^3$.

### (e) Materials

The technology adapts to use of non-metallic materials of construction, therefore giving good benefits in maintenance and operation life.

### (f) Low operations and maintenance costs

The range of energy usage is shown below:

Sea water: 20 - 30 kWh/1,000 gal
Brackish water: 4 - 12 kWh/1,000 gal

## 4. Disadvantages

### (a) Non-forgiving membrane

The membranes are sensitive to abuse. If they are not taken care of, they will probably fail. This is the major disadvantage of reverse osmosis for use in very small systems that receive little care. Design considerations can be included to minimize the problem, such as fixed recovery.

(b) Pre-treatment

While not any different from other desalting processes, reverse osmosis works best with a steady brine concentration; therefore the chemistry of the feed water must be controlled to ensure long membrane life.

## 5. Economics

The economics of the process deserves important consideration. The cost of reverse osmosis systems have not followed world inflation.

The capital costs today of brackish water systems complete, installed with building, are as follows:

| Capital cost (in U.S. dollars per gpd of installed capacity) | Capacity range (in gpd) |
|---|---|
| $1.50 | 60,000 to 100,000 |
| 1.00 | 500,000 to 1,000,000 |
| 0.78 | 7,000,000 |

The operation and maintenance costs for these brackish plants will run from $.85 to $1.00 for each 1,000 gallons of water produced. This allows for the membrane to be replaced every five years. The membrane replacement allowance is from $0.11 to $0.15 per 1,000 gallons of water produced. These costs are calculated based on electricity costing $0.07/kWh.

The capital cost of desalting sea water by reverse osmosis has been moving on a downward trend as new membranes are developed. There generally are $3.00/gal/day per gpd of installed capacity for plants in the range of 60,000 to 100,000 gal per day and $6.00 for smaller plants. Total operation and maintenance for small plants is around $4.00 to $4.50 per 1,000 gal of water produced with larger plants having a lower cost of $3.50 to $4.00/1000 gal. Fluctuating energy prices and labour costs can have a marked effect on these costs.

It has been a buyers' market for desalting by reverse osmosis. Overly keen competition has produced bids on larger plants (1 mgd and greater) which have been very close to or under actual construction costs. This in turn has created delays on some projects along with quality cuts and other long term problems for the user.

## 6. Summary

Reverse osmosis is a viable tool for desalting brackish and sea water today. Research on new membranes is directed toward increased salt rejection at lower operating pressure, therefore decreasing energy requirements for removing a pound of salt. Systems research is directed toward more foolproof pretreatment, which translates into longer membrane life and increased operational efficiencies. New techniques are under consideration to recover waste energy on large installations.

Reverse osmosis can and will play an important role for the production of usable fresh water for people, industry and agriculture in the developing countries throughout the world in the years to come.

## D. Desalination with renewable energy sources

by T.A. Lawand*

### 1. Introduction

For a desalination process to be feasible, there must be no viable local source of exploitable fresh water, be it in the form of surface water (lakes, rivers, basins), ground water or even collectable rain water. Unless the utilization of these local fresh-water supplies are fully exploited, then the use of desalination processes is unjustified. Once the desirability of using some form of desalination process has been established, it is essential that certain factors of production be present, so as to ensure the appropriateness of this system. These factors are listed in table 6.

Table 6. Factors of production needed for desalination process

1. Source of saline or brackish water
2. Available form of energy
3. Capital for investment in plant
4. Management and control
5. Skilled labour
6. Maintenance facility (spare parts, etc.)
7. Reasonable accessibility

It can be seen from table 6 that energy is only one factor in the overall process. From a cost viewpoint, it is not necessarily a limiting or dominant factor. There was an increase in the cost of energy, following the 1973 fuel oil price escalation. However, in recent years, the price of energy has been levelling off, reducing energy costs as part of the total charges in a desalination process.

Generally, labour, capital investment and maintenance requirements, can be equal to or greater than, energy costs. Nonetheless, it is important to ensure that desalination plants not be placed in locations where the cost of energy is prohibitive. In addition, should the supply of energy be dubious or difficult, then the importance of this factor will become dominant, as there can be no desalination process, without some input of energy.

The role of energy in the desalination process is certainly not the subject of this paper, as this topic has been dealt with adequately by more competent investigators in the past. Please refer to the References to this paper which have been compiled to indicate the breadth of work that has been done in this field.

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Energy is nonetheless an important criteria in the production process. Considerable effort is being made to reduce the equivalent energy consumption per cubic metre of fresh water produced in a desalination plant. This is illustrated in table 7. One can see that there is a significant difference in unit energy consumption between membrane processes, such as reverse osmosis and electrodialysis, and distillation processes. Simple solar distillation is of course the most energy-demanding process per unit of production in that the level of operation is so basic.

The prime topic of this paper is to determine the role of renewable energies in meeting the energy needs of desalination processes. As indicated, table 7 lists some of the energy levels used in different desalination processes. It can be seen that there are significant variations in these levels. Nonetheless, as a basic rule, the amount of energy required is so significant, that using low density energy sources, such as solar or wind energy, needs very careful consideration. In fact, there are certain upper limits of capacity which cannot be surpassed using low density energy forms such as renewable sources of energy.

(a) References

The literature is replete with references on the use of renewable energies for desalination purposes. One aspect of this brief review article is to provide some references for this subject in general. It should be noted however that the subject, on an international scale, is enormous. Even the various desalination abstracting journals are incomplete in this regard as more references exist than can be compiled in one location. The list of references therefore contains a series of older and more recent references on the use of renewable energies for desalination purposes.

References on traditional simple solar stills, which have by far the widest application, albeit for small scale production, have not been specifically referenced, because the volume of references is enormous and that sub-section is quite well known to desalination authorities in the field. It is dealt with separately in this paper.

The two publications cited in the References by O.K. Buros are by far the most complete publications specifically dealing with the use of renewable energies in desalination processes; in fact the first is a chapter of the excellent USAID Desalination Manual published in August 1980. This report covers the field far more thoroughly than any previous report in that it surveys all renewable energy sources and their utilization for desalination purposes. It should be noted that one of the problems with desalination systems is that they are generally small, and keeping track of their performance is often a difficult task. The desalination information referred to concentrates on energy conversion processes, such as solar energy to heat, solar energy for electricity, wind energy for electricity or to mechanical shaft power, etc. in addition to the particular desalination process being undertaken. Table 8 abstracts information from these and other reference sources so as to cite specific examples of some of the renewable energy-powered desalination systems currently being utilized.

Table 7. Comparison of equivalent energy usage in various desalination systems

| Desalination process | Equivalent energy consumption (kWh/m$^3$ of fresh water produced) | Reference |
|---|---|---|
| **Reverse osmosis plants** | | |
| Brackish water | 1.9 to 3.2 | Buros and others, 1980, |
| Sea water | 7.9 to 10.6 | USAID Desalination Manual |
| Potential energy recovery | up to 2.6 | pp. 5-24. |
| Sea water | 4.8 to 6.4 | Vaillant, Dessalement |
| Brackish water | 3.5 to 4.5 | de l'eau de mer. |
| Brackish water | 0.53 | World Water, Oct. 1984 |
| **Hyperfiltration** | | |
| Flour-UCLA | 3.2 | Speigler, Table 8.9 |
| General Dynamics | 9.2 | p. 424 |
| Aerojet | 8.2 | |
| Aerojet | 2.3 | |
| General | 6.3 | |
| **Distillation processes** | | |
| Simple distillation | about 1000 | Vaillant, Dessalement |
| Multiple effect distillation | 57 to 62 | (electric & fuel energy) |
| LTV Distillation | 66.5 | " " |
| Vapour compression | small units: 75 to 100<br>larger units: 53 | |
| **Electrodialysis** | | |
| Webster Plant USA | 2.4 | Speigler (as above) |
| Buckeye Plant USA | 2.9 | |
| Two Indian Plants | 4.2 | Conf. on Water Desalination, India. |
| Brackish water | 1.6 to 5 | Vaillant (as above) |
| Sea water | 10 to 45 | |
| **Solar distillation** | about 1250 | by estimation |
| **Freezing processes** | | |
| Direct contact | 8 to 15 | Vaillant, Dessalement de l'eau de mer. |
| Indirect contact | 8 to 10 | |

Note: The figures quoted are transcribed from the references as cited by the authors. The variations are considerable.

Table 8. Some operating renewable energy desalination systems

| Type of system | Capacity ($m^3$ of fresh water produced per day) | Energy requirement ($kWh/m^3$ fresh water per day) |
|---|---|---|
| Wind powered reverse osmosis systems | | |
| North Sea, Federal Republic of Germany | 10.4 | 11.1 |
| France | 12.0 | (predicted) 7.5 |
| Solar distillation | | |
| La Gônave, Haiti | 1.1 | |
| Puerto Chale, Mexico | 1.0 | |
| Awania, India | 4.9 | |
| Solar Multi-stage flash | | |
| La Paz, Mexico | 9.8 | |
| Solar Photovoltaic RO | | |
| Cadarache, France | 54.4 | |

## 2. Renewable energy sources

There are a variety of renewable energy sources which can be used for desalination purposes. Obviously not all renewable energy sources are suitable for desalination purposes. In order to be appropriate they must satisfy the following basic criteria:

i) The renewable energy form must be freely available to the desalination plant operator.

ii) The renewable energy form must be available at the times when desalination is required.

iii) The energy conversion process which transforms the renewable energy source into a useful form for the particular desalination process must of necessity be managed and controlled by the desalination operators.

iv) The renewable energy conversion technology must be sufficiently mature so as to ensure proper reliability of the desalination plant in the field.

Specific renewable energy forms and their availability are discussed below. However, it should be noted that solar energy is the most widespread of these energies. It is primarily available in the form of low grade energy. Most solar desalination efforts to date have been aimed at transforming this energy directly into heat, primarily for the distillation processes. More recently, solar energy has been converted to electricity (solar photovoltaic effect) or mechanical power (solar thermal pumps) which can be used to generate other desalination systems.

Other forms of energy, such as biomass energy, can also be converted directly into heat or transformed into mechanical shaft power. Wind energy is primarily available in the form of mechanical shaft power which can either be used directly in this form or converted into electricity or heat, whichever is required for the specific desalination project. Each of these energy forms is discussed briefly below with the greatest emphasis being placed on solar and wind energy respectively.

### (a) Solar Energy

Desalination is generally required in arid and semi-arid regions of the world. These areas are normally characterized by lengthy dry periods and short rainy seasons and higher-than-average levels of solar radiation intensity. Some examples of typical arid zone solar radiation levels are cited below:

Annual mean solar radiation on the horizontal in watt hours/square metre

| | | | |
|---|---|---|---|
| Aden | 6006 | Pakistan (Karachi) | 5132 |
| Australia (Sydney) | 4446 | Philippines (Quezon) | 4516 |
| Colombia (Bogota) | 4691 | Senegal (Dakar) | 5331 |
| Burma (Rangoon) | 5505 | Sri Lanka (Colombo) | 5796 |
| Chile (Atacama Desert) | 7159 | Sudan (Khartoum) | 5091 |
| Egypt (Giza) | 5622 | Thailand (Bangkok) | 5063 |
| Hong Kong | 4377 | Trinidad (Port of Spain) | 5634 |
| India (Ahmedabad) | 6076 | Tunisia (Tunis) | 5121 |
| (Madras) | 6134 | USA (Tampa, Florida) | 5285 |
| Kenya (Nairobi) | 5494 | USSR (Tashkent) | 4248 |
| Mauritania (Nouackchott) | 6507 | Pacific Ocean (Wake Island) | 6495 |
| Nigeria (Kano) | 5238 | | |

These examples give average levels of radiation intensity over the years on the horizontal. This information can be used, when more detailed daily and monthly measurements are available, for example, for the estimation of tent type solar stills which are directly ground mounted. It can be seen that there is not a significant variation between most of these locations on an annual basis. There are some priority locations in which solar radiation intensity is extremely high. This is indeed true of much of the Middle East and coastal desert areas.

On the other hand, variations during the year can be as high as 50 per cent from one month to another. These monthly average variations are more significant at higher latitudes, and tend to dampen out closer to the equator.

If solar energy is used to heat sea water, for example, then solar collectors are used which face the equator, providing an increased amount of solar radiation on the incident surface. Once solar collector arrays become large, they tend to become considerably unwieldly and costly. Every attempt must be made to reduce the complexity of solar energy systems so as to obtain better performance efficiency and cost effectiveness.

Solar Collectors Systems. A solar collector differs in several respects from more conventional heat exchangers. The latter usually accomplish a fluid-to-fluid heat exchange with high heat transfer rates and with radiation as an unimportant factor. In the solar collector, energy transfer is from a distant source of radiant energy to a fluid.

There are different types of solar collectors namely i) Flat Plate, ii) Heat-Pipe, iii) Concentrating, iv) Heliostat/Central receivers.

Flat plate collectors use both beam and diffuse solar radiation and do not require tracking of the sun. They also require little maintenance. They are mechanically simpler than concentrating collectors and their output is delivered at moderate temperatures, up to perhaps 100°C above ambient temperature.

Heat-pipe type collectors are a variation of the flat plate collector. The conventional flat plate collector is modified so that the fluid conduits are replaced by an array of heat pipes with their condensing ends suitably attached to a fluid heater pipe in which flows the saline water. Heat-pipe type solar collectors are typically not only corrosion proof and less likely to suffer from leakage, they are also freeze proof (should this ever be a required feature).

Many designs have been set forth for concentrating collectors depending on the requirement to deliver energy at higher temperatures. The concentrators can be reflectors or refractors, can be cylindrical etc. and can be continuous or segmented. Receivers can be convex, flat or concave and can be covered or uncovered.

The concentration ratios can be from low values of 1.5 or 2 to high values of the order of 10,000. However, the higher the concentration, the greater the precision needed to track the sun. Whether the tracking is done intermittently, or continuously and either manually or automatically depends upon the temperature of the output needed. The energy required for tracking must be accounted for when calculating the efficiency either of the collector or of the system.

Heliostats are arrays of individually mounted and synchronized reflectors focusing solar radiation onto a central receiver. The high temperatures generated can be used to power virtually any desalination process. A number of these systems have been built but none have as yet been applied for desalination purposes.

(b) Wind energy

Energy is available in the wind if a wind turbine is used to harness the energy. This machine is similar to a water turbine except that it operates in the air. Because air density is comparatively lower than water, the rotor diameters are relatively larger for wind turbines than for water turbines. (The density of air is = 1.29 $kg/m^3$ while the density of water is 1,000 $kg/m^3$).

The total power available in the moving wind is: $P = 1/2\ p\ AV^3$ where p = density of air, A = swept area, and V = free stream air velocity. However, only 16/27 of this total power is theoretically extractable. Because of aerodynamic imperfections in any practical wind machine and due to mechanical and electrical losses, the actual power extracted is less than the theoretical.

There are various kinds of rotors, each with its own characteristics based upon the shaft position, mechanism for tracking the wind, type of blades and their materials of construction, the solidity ratio, etc.

The higher the solidity ratio, the better the starting torque, but lower the tip speed ratio; also the lower the solidity ratio, the higher the tip speed ratio but lower the torque. Water pumping windmills typically have high solidity ratios, to have enough initial starting torque; and electrical generating windmills have low solidity ratio to obtain the high rotational speeds needed for electricity production. Generally, the efficiency of the windmill rotor is positively dependent on the tip speed ratio.

Table 9. Power available in the wind (kilowatts)

| Wind speed (m/s) | Rotor diameter (m) 3.81 | 7.62 | 15.24 | 30.48 | 60.97 |
|---|---|---|---|---|---|
| 4.50 | 0.38 | 1.5 | 6.0 | 24 | 96 |
| 9.17 | 3.08 | 12.3 | 49.2 | 196 | 784 |
| 13.75 | 10.40 | 41.6 | 166.4 | 666 | 2,664 |
| 18.33 | 24.60 | 98.4 | 393.6 | 1,574 | 6,296 |
| 22.92 | 48.20 | 192.8 | 771.2 | 3,085 | 12,340 |
| 27.50 | 83.20 | 332.8 | 1,331.2 | 5,325 | 21,300 |

Source: Modified from E.W. Golding, The Generation of Electricity by Wind Power (London, E. & F.N. Spon, Ltd., 1955).

Notes:

$P= 0.593\ K.AV^3$ in kilowatts

$K= 0.00064$

Moreover, the structure that is holding the rotor should be sufficiently rigid to support it against high wind gusts. A suitable safety mechanism is necessary to protect the machine under stormy wind conditions.

In remote areas, where desalination plants might normally be operating, it is worthwhile to explore the possibilities of using windmills for pumping operations. Simple sail windmills or sophisticated, electricity generation types both have a role to play.

For supplying the process of desalination itself, some electric wind generators are currently being utilized. The electricity produced directly operates the desalination plants. A number of interesting studies have been undertaken indicating that it is possible to connect a windmill directly to the high pressure pump of a reverse osmosis system.

As usual, like other renewable energy resources, wind is highly variable and is not always available. Hence suitable storage systems might have to be incorporated, such as storing pumped water in overhead tanks or storing the electricity in battery banks.

There is no such thing as the most suitable windmill; it is always a case of finding the one which best suits a particular situation. Especially in the remote areas where conventional energy sources are not available or competitively priced, conditions can be more conducive to the use of wind machines, if the wind regime is adequate. Typically, locations with windspeeds in excess of 4 m/sec can be considered for wind machine installation.

Some of the most likely places where wind machines could provide energy for a desalination system are coastal regions or islands, where there is abundant saline water and adequate wind velocity for most of the year.

A list of some examples of average annual wind speeds is given below:

| Location | Average Wind Speed (m/sec) |
|---|---|
| Perth, Australia | 5.4 |
| Sydney, Australia | 3.5 |
| Buenos Aires, Argentina | 4.4 |
| Victoria Point, Burma | 2.4 |
| Ahmedabad, India | 3.3 |
| Bombay, India | 6.3 |
| Gopalpur, India | 3.6 |
| Madras, India | 4.8 |
| Ramallah, Jordan | 5.4 |
| Tripoli, Libya | 4.3 |
| Karachi, Pakistan | 5.2 |
| Ste Helena | 7.7 |

(c) Other forms of renewable energy

Biomass energy is less likely to be available to power desalination plants in a desert region, principally because it is very unlikely that surplus renewable biomass (such as wood, agricultural residues, etc.) will be found as a low cost item in arid areas. It is essential therefore, to relate the appropriateness of the renewable energy form to the climatic and geographic limitations imposed by location.

The same holds true for hydraulic energy, as it is unlikely to find rivers in those areas concurrent with the need for saline water desalination. In some isolated island locations some energy could be extracted from swift moving sea currents, if indeed these were available and easily exploitable. However the cost of such systems is still prohibitive. Some small-scale attempts have been made to use wave power for desalination purposes.

Sufficient renewable energy forms are generally available in different arid locations around the world; however, care must be taken that the extractable energy is available in adequate amounts and that the extraction technology is adapted to the particular situation.

In all cases, a very careful assessment of the problem is necessary before applying known solutions. This has not always been the case in the application of renewable energy powered desalination systems in developing areas.

## 3. Use factors with renewable energies

Before considering the use of windpower as a desalination energy source, one must be absolutely sure that sufficient data is available on the wind regime so as to be able to predict the performance of wind turbines in the particular locality in question.

The same is true for the use of solar energy or any other renewable form of energy. There is no difference from the use of conventional energy sources such as electricity or fuel oil. One would not plan a conventional MSF distillation plant without ensuring an adequate and available source of electricity or fuel. By the same token therefore, the design engineer contemplating the use of renewable energy sources for desalination purposes must ensure that appropriate climatological instrumentation has been used in the area to measure the levels of solar radiation and wind speeds. As a result of these measurements, some estimates of renewable energy availability can be established for design purposes.

Storage of renewable energy, to permit continued fresh water production when the energy resource is inadequate can add additional costs and complexities to the desalination system. Simple solar still basins typify the appropriateness and adaptation of technology to a renewable energy source of variable intensity in that use is made of the solar energy when it is available, only. During sunny periods, some storage takes place of the heat in the water, allowing distillation to occur at night when one third of the distillate is produced. However, in other instances, in order to increase the productivity of solar stills, attempts have been made to reuse the latent heat of condensation. However, this only increases the complexity of the plant. A better way perhaps is to preheat saline water during the day (which might be the cooling water of a diesel electric generator) and feed it into a solar still at night, using the still for nocturnal production.

Most of the technologies used to date largely exceed the complexities of the simple solar still. While the latter is not without its drawbacks (particularily the large land area requirements), if well engineered and constructed, and well managed, it can produce fresh water for many years. The newer technologies rely on the production of heat from solar energy, to run smaller, multiple effect distillation plants, or freeze separation plants. Small reverse osmosis plants are run using solar photovoltaic panels or wind electric generators. In all cases, the complexity must be justified by reliability and increased productivity.

The possibility of augmenting fresh water production through the collection of rain water on the surfaces of the solar still basins should be given priority attention in all cases. This is essential in that generally, rain water can be consumed adequately if proper precautions are taken. As has been seen earlier, renewable energy sources are basically low density sources, in that they can never be expected to compete with high density energy forms for the production of large scale quantities of fresh water.

Finally it must be stressed that the use of local resources such as renewable energies means that the desalination system must be operated and managed by a well-organized structure to ensure success.

## 4. Use of desalinated water

Finally, it is essential in considering any desalination process (which should only be undertaken when a thorough exploitation of all available fresh water collecton means have been exhausted), that a fresh water use policy must be initiated to avoid, for example, costly desalinated water being wasted. Some indication of human and agricultural fresh water requirements are given in table 10.

Table 10. Fresh water requirements

| Purpose | Desalinated Water Consumption (litres/day) | Max. Salt Content (mg/litre) |
|---|---|---|
| Human Drinking and Culinary | per person | |
| Absolute minimum | 4 | 3,000 |
| Minimum | 7.5 | 3,000 |
| | | Desirable Content |
| Minimum in extreme heat | 11.4 | 1,000 |
| Animals Drinking | per animal | |
| Sheep | 5.7 | 12,500 |
| Horse | 3.9 | 6,000 |
| Cow, Steer | 45.4 | 9,000 |
| Cow in milk | 95.0 | 9,000 |
| Irrigation | per hectare | |
| All purposes | 15,600 | 500 |
| Limit of tolerance | 21,000 | 3,000 |
| Batteries | Small quantities | 0 |

Source: G.T. Ward, Possibilities for the Utilization of Solar Energy in Underdeveloped Rural Areas (Rome, FAO Working Bulletin No. 16, 1959).

It can be seen from the above that fresh water produced from a distillation plant, which usually has very low salt content, can be mixed, particularly with brackish water, to increase the overall productivity of the plant. This should only be done if the brackish water is not biologically contaminated. It is essential that desalination plants improve the quality of drinking water and this should never be forgotten or overlooked.

It is therefore highly recommended that any desalination system utilizing renewable energy sources, be necessarily combined with a suitable fresh water management policy which would ensure that the fresh water, so precious to the needs of the community, both from a human and commercial productivity point of view, are adequately used. It is parallel to the major programmes that have gone on in industrialized areas for reducing the energy consumption in buildings. Such energy conservation progrmmes have made significant impacts on the energy consumption patterns in industrialized areas. Water conservation policies must also be adapted and major consumers of fresh water such as flushing sanitary facilities, should wherever possible, be replaced by other means, not requiring copious quantities of fresh, desalinated water. In this way the community can reap maximum benefit from the desalination plant and can indeed in many instances seriously consider the use of renewable energy sources where overall consumption of fresh water has been significantly reduced.

## 5. Available technologies

Many systems are marketed around the world on renewable-energy-powered desalination units. These use primarily solar and wind energy.

One of the recent developments of interest is the adaptation of small-scale Reverse Osmosis (RO) units to renewable sources of energy. The need for small-scale quantities in remote areas and for emergency relief has spawned the development of a number of commercially available systems consisting of a high pressure pump, RO modules and sometimes energy recovery units which can be powered either: by hand; by wind energy; or by solar energy.

### (a) Manual or hand-powered

The hand-powered systems vary in complexity from one manufacturer to another. Seagold Industries in Vancouver, Canada, market a small manual water maker, which can produce 6 litres of fresh water per hour.

These manually-powered desalinators are destined for remote locations or they could indeed be used by individual families. With a capacity of approximately 6 litres/hour, it is unlikely that an individual would be able to pump continuously at this rate for any length of time. Therefore, one cannot expect to obtain large volumes of fresh water from small units of this type.

### (b) Mechanical drive linked to windmill

A similar type of unit using wind power is illustrated in figure 9, which shows a small unit made by Tecobin Inc., Laval, Canada. This incorporates a pivoted wind scoop and shroud, and a horizontal wind turbine arrangement. The unit is approximately 1.2 cubic metres in volume. The daily capacity, much like the hand-powered unit, is on the order of 25 litres in a wind speed of under 10 kilometres per hour. Reverse osmosis modules produce pure drinking water directly from sea water.

### (c) Solar-powered systems

Figure 10 shows an illustration of a solar powered desalination system using multiple effect distillation.

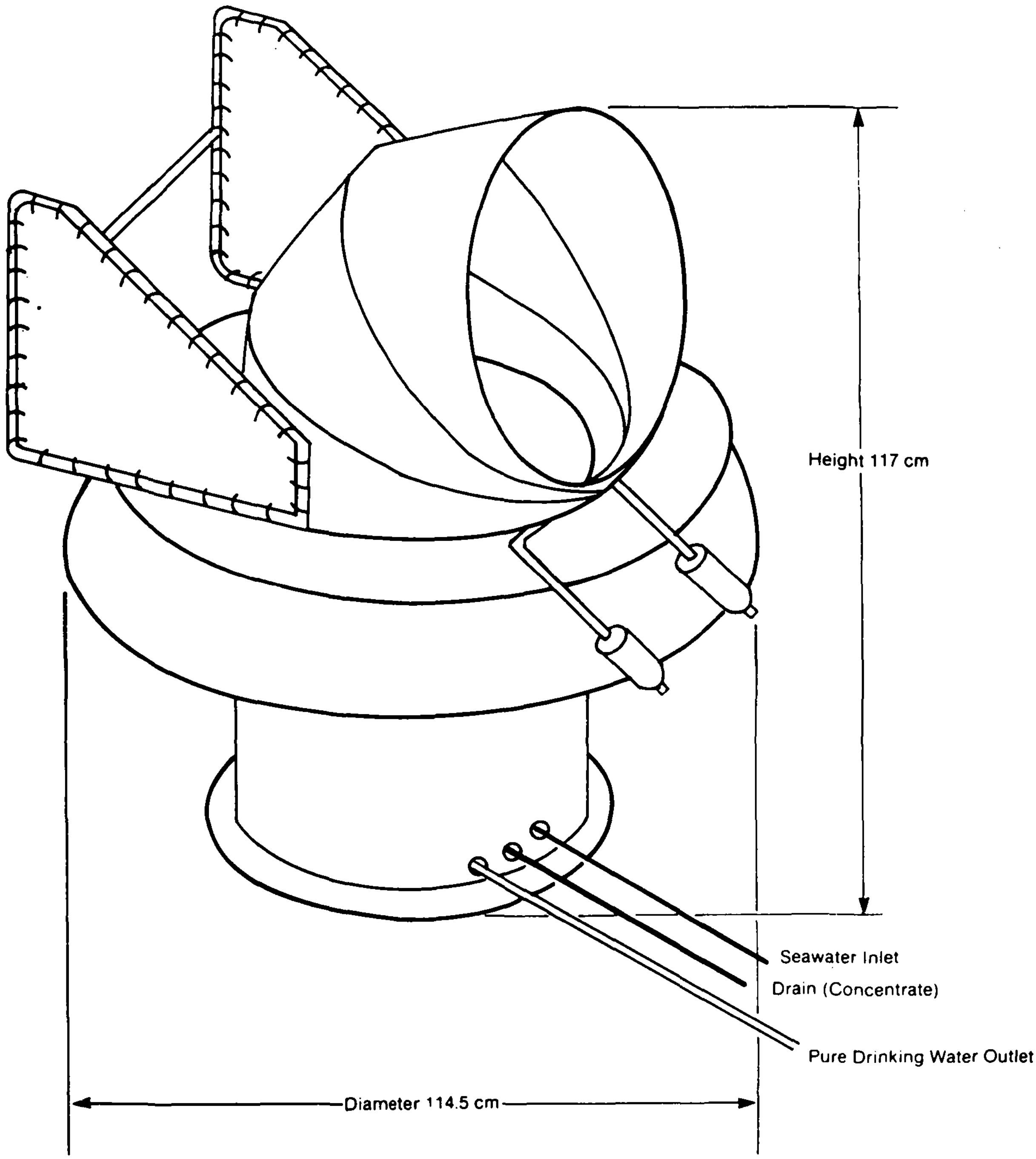


Figure 9. Small-scale wind-powered reverse osmosis unit

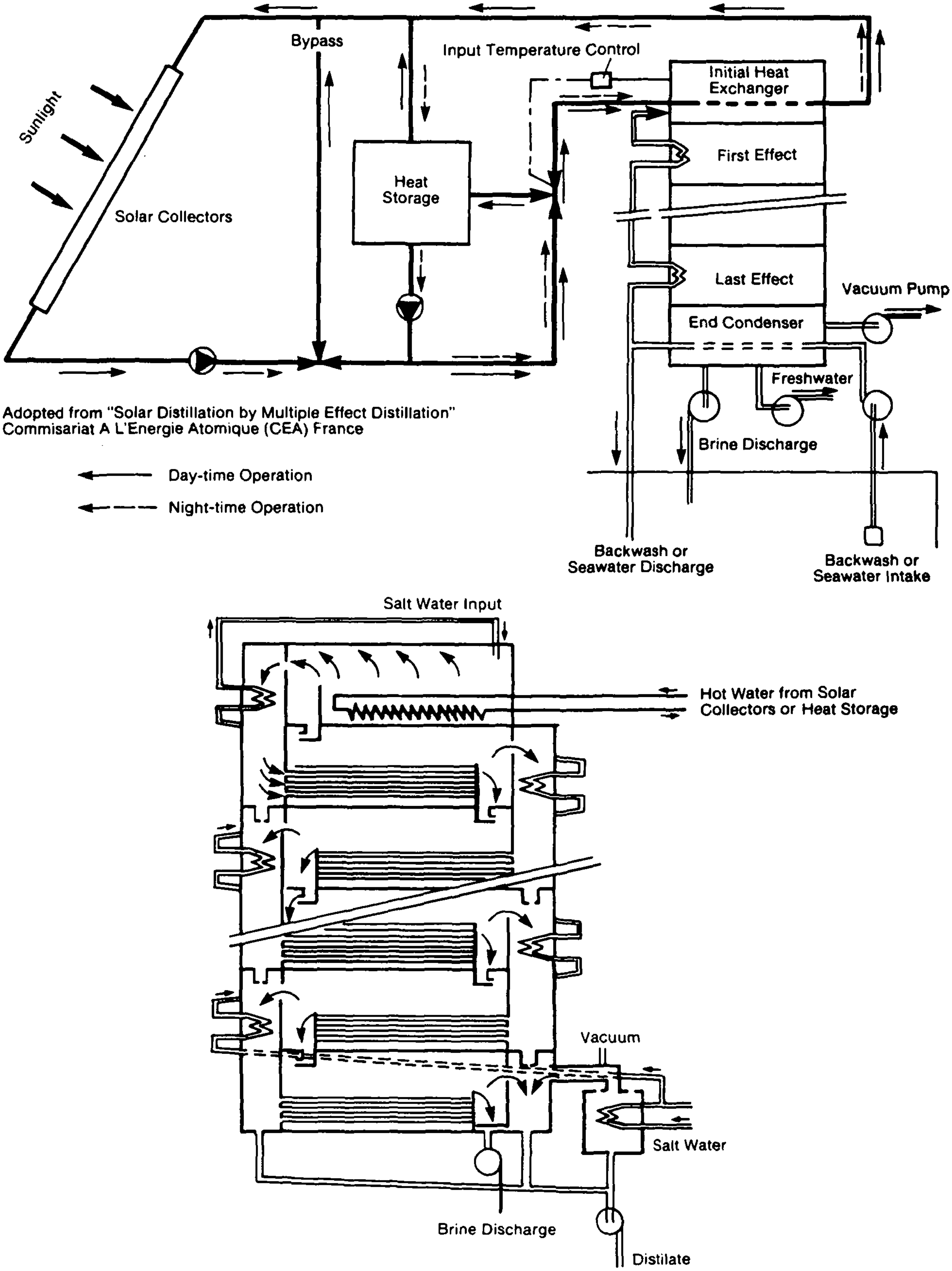


Figure 10. Solar powered desalination unit

By far the most widespread of small-scale solar systems is the simple solar still. A wide number of these are in use around the world from very small installations to the somewhat larger units indicated in table 8. The technical components which make up solar distillation systems are varied. There are many reports which cover adequately the different designs and types that are available. A cross-section view of a simple solar still installed in Haiti is shown in figure 11. This type of still is designed for installation on very flat land so as to provide some height for the drainage and gravity flow of the distillate and sea-water feed.

Costs of such systems vary enormously depending on the costs of labour and materials at any given site. Costs can include everything from site preparation, materials, the transportation of materials to the site, ancillary equipment and the training of personnel. The lack of available skilled personnel for supervision invariably means that the costs run much higher than predicted. As an example, a recently built solar still in Haiti costs on the order of \$US 150/m$^2$ installed, which is roughly four times the anticipated costs. The size of this still is just over 100 square metres. It should be pointed out that amongst the reasons for the cost overrun of a full 30 per cent was the hiring of a local engineer to supervise the installation. The costs also increased roughly 20 per cent when skilled workmen were hired to do the jobs that could have been largely handled by the local population. Poor organizational management can lead to severe cost overruns.

(d) The Soleras solar energy desalination project

One of the prime projects conceived for the use of the utilization of renewable energy technologies for desalination purposes is the SOLERAS Solar Energy Project - a joint Saudi Arabian/United States effort.

Table 11 illustrates the project proposals - with two brackish water treatment plants being scheduled for the United States and three sea water desalination plants for Saudi Arabia. The data provided by W. Luft and M. Al Nemer, 1982 indicate that the average daily capacity of the plants is 6,000 m$^3$ of fresh water.

The proposed installed capacity of the plants would be miniscule compared to the mammoth installations of multi-stage flash distillation facilities at Al Khobar and Al Jubail in Saudi Arabia of 250,000 m$^3$/day and 1,100,000 m$^3$/day respectively.

It is therefore clearly illustrative of the limitation of renewable energy sources. The inherent danger placed in projects of this nature is that relatively new, somewhat immature renewable energy technologies are being touted for the provision of fresh water, a commodity indispensible for normal life and commercial activity. It is problematic whether this type of approach is appropriate for consideration under these circumstances. It is noteworthy that the Saudi Arabian authorities have taken a bold step through the incorporation of such futuristic renewable energy systems for desalination processes. The world must wait the 5 or 10 years necessary to determine if indeed these renewable energy systems can be relied upon to adequately provide assured quantities of fresh water.

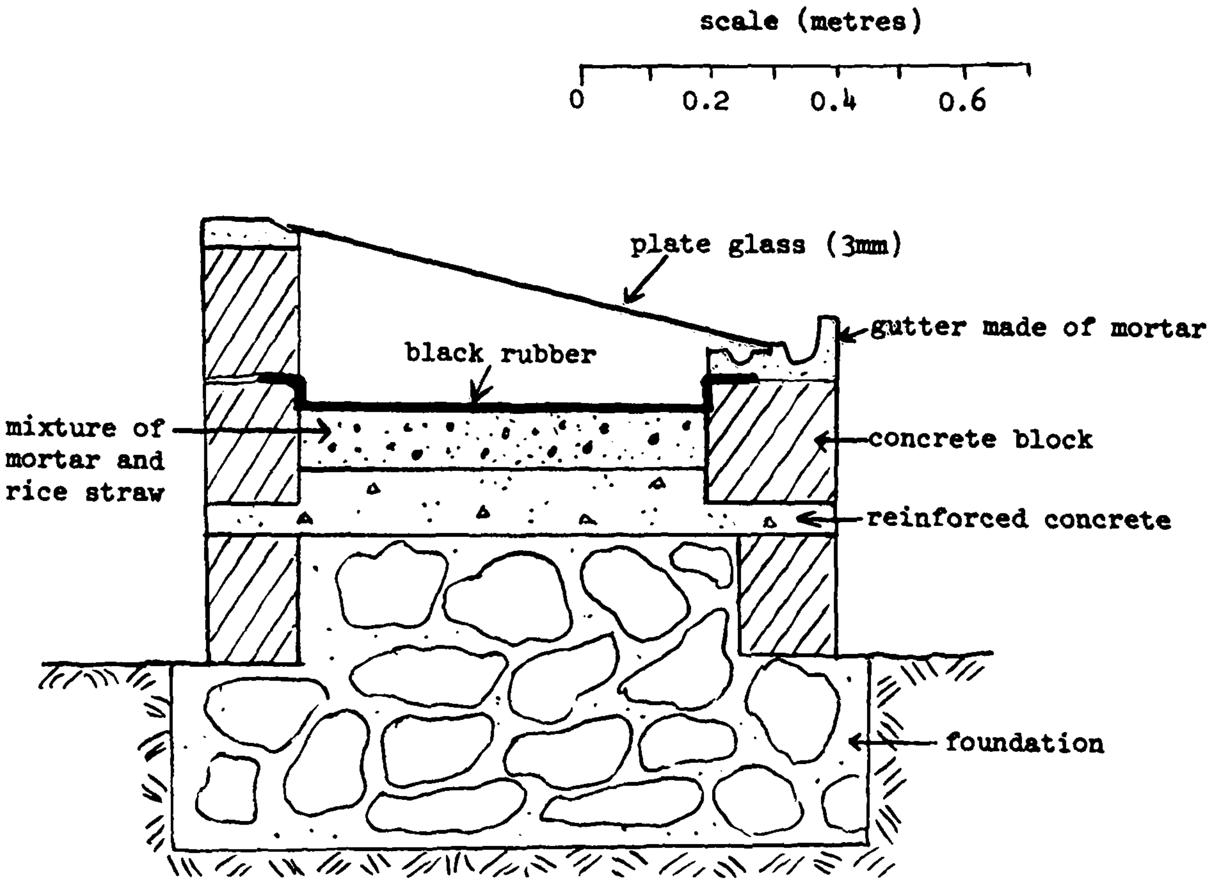


Figure 11. Simple solar still installed in Haiti

Table 11. Proposed SOLERAS desalination systems

| Desalination technology | Solar Energy technology | Location | Collector area ($10^3$ $m^2$) | Collector efficiency[a/] | Incident energy per unit product wtr. (kWh/$m^3$) | Collected energy per unit product wtr. (kWh/$m^3$) |
|---|---|---|---|---|---|---|
| Brackish | | | | | | |
| One-stage RO | Heliostats and central receiver | Rankin, Texas | 20.5 | 0.50 | 21.3 | 9.7 |
| Two-stage RO in series | Wind generators and line focus thermal | Brownville, Texas | 9.3 (W)<br>12.8 (TH) | 0.52 (W)<br>0.42 (TH) | 18.9 | 7.1 |
| Sea water | | | | | | |
| Indirect freezing | Point-focus thermal collectors | Yanbu, Saudi Arabia | 43.8 | 0.72 | 74.0 | 49.3 |
| One-stage RO in series with ED | Line-focus thermal collectors & photovoltaics | Yanbu, Saudi Arabia | 56.0 (TH)<br>5.0 (PV) | 0.48 (TH)<br>0.09 (PV) | 75.8 | 30.5 |
| Two-stage RO in parallel with 24-effect distillation | Heliostats & central receiver | Yanbu, Saudi Arabia | 22.7 | 0.67 | 38.0 | 17.4 |

Source: W. Luft and M. Al Nemer, 1982, "The Soleras Solar Energy Desalination Project," Sun World (6:1:10-12).

Notes:
Brackish water salinity is 6,000 ppm total dissolved solids and sea-water salinity is 44,000 ppm.
W = Wind; TH = Thermal; PV = Photovoltaics; RO = Reverse Osmosis; ED = Electrodialysis

a/ Total energy collected divided by direct (total for PV) incident energy

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## E. Factors influencing the economics of desalination

by James D. Birkett*

### Introduction

The background document for this Conference (Water Series No. 14) probably contains as much economic data as most interested parties would need. However, there are several ways of considering that information, as well as supplementary data which may be useful as well. The following tables and figures elaborate upon the background document and suggest several conclusions which may be drawn.

*Arthur D. Little, Inc., 15 Acorn Park, Cambridge, MA 02140.

Table 12. Typical sea water desalting plant costs, 3,800 $m^3/d$ (1 mgd) facility

| CAPITAL COSTS[a/] | MSF | MED ($/$m^3$/day) | SWRO |
|---|---|---|---|
| Direct capital | 1,600 | 1,350 | 1,125 |
| Indirect capital | 1,075 | 775 | 300 |
| Total capital | 2,675 | 2,125 | 1,425 |
| OPERATING COSTS[b/] | | ($/$m^3$) | |
| Operation and maintenance | 0.81 | 0.79 | 0.98 |
| Fixed charges | 1.56 | 1.24 | 0.83 |
| Total water costs | 2.37 | 2.03 | 1.81 |

Source: United Nations Department of Technical Co-operation for Development, Use of Non-conventional water resources in developing cuntries, Natural Resources/Water Series No. 14 (New York, United Nations, 1985)

Notes:
MSF = Multi Stage Flash; MED = Multiple Effect Distillation; SWRO = Sea water Reverse Osmosis.
a/Capital cost in 1981 U.S. dollars per cubic metre/day of installed capacity.
b/Operating costs in 1981 U.S. dollars per cubic metre of water produced.

Table 13. Typical brackish water desalting plant costs, 3,800 $m^3/d$ (1 mgd) facility

| | RO | ED |
|---|---|---|
| CAPITAL COSTS | $/$m^3$/day | $/$m^3$/day |
| Direct capital | 250 | 325-375 |
| Indirect capital | 75 | 75-100 |
| Total capital | 325 | 400-475 |
| OPERATING COSTS | $/$m^3$ | $/$m^3$ |
| Operation and maintenance | 0.24 | 0.15-0.22 |
| Fixed charges | 0.16 | 0.21-0.25 |
| Total water costs | 0.40 | 0.36-0.47 |

Source: United Nations Department of Technical Co-operation for Development, 1985, ibid.
Notes:
RO = Reverse osmosis; ED = Electrodialysis.
Costs in 1981 US dollars.

Table 14. General cost ranges for desalination

(1) Over-all rough costs (including capital recovery) of

$0.25 - $0.50/$m^3$ for brackish feed water
$1.30 - $3.50/$m^3$ for sea-water feed

in size ranges of 2,000 - 40,000 $m^3$/day if built in the United States.

(2) Small units built in developing countries could roughly double cost.

(3) Special feed water and brine disposal development work could add $0.25 - $1.30/$m^3$.

Source: United Nations Department of Technical Co-operation for Development, 1985, ibid.

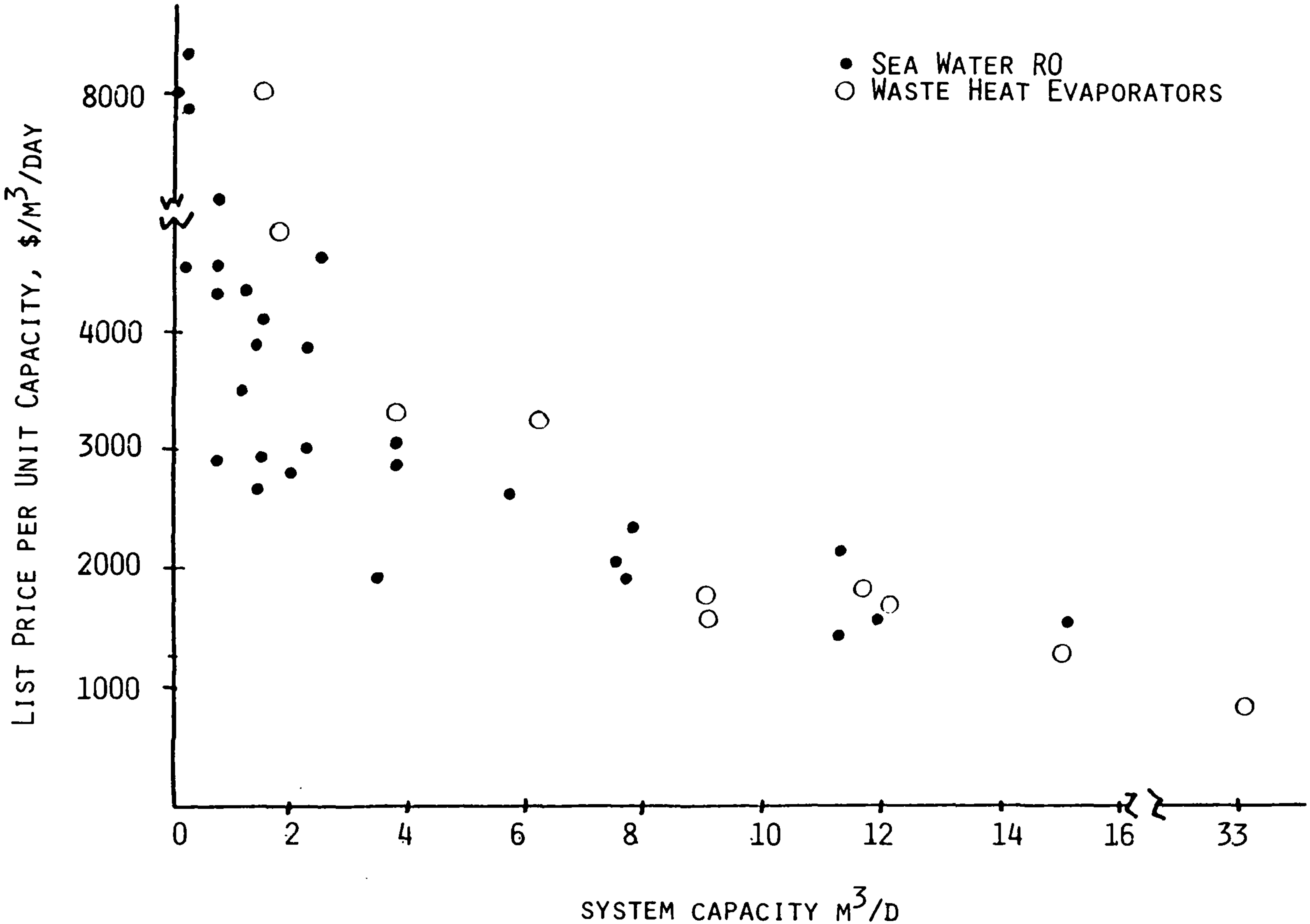


Figure 12. Initial cost of some small marine desalinators on the market

Source: Arthur D. Little, Inc. literature.

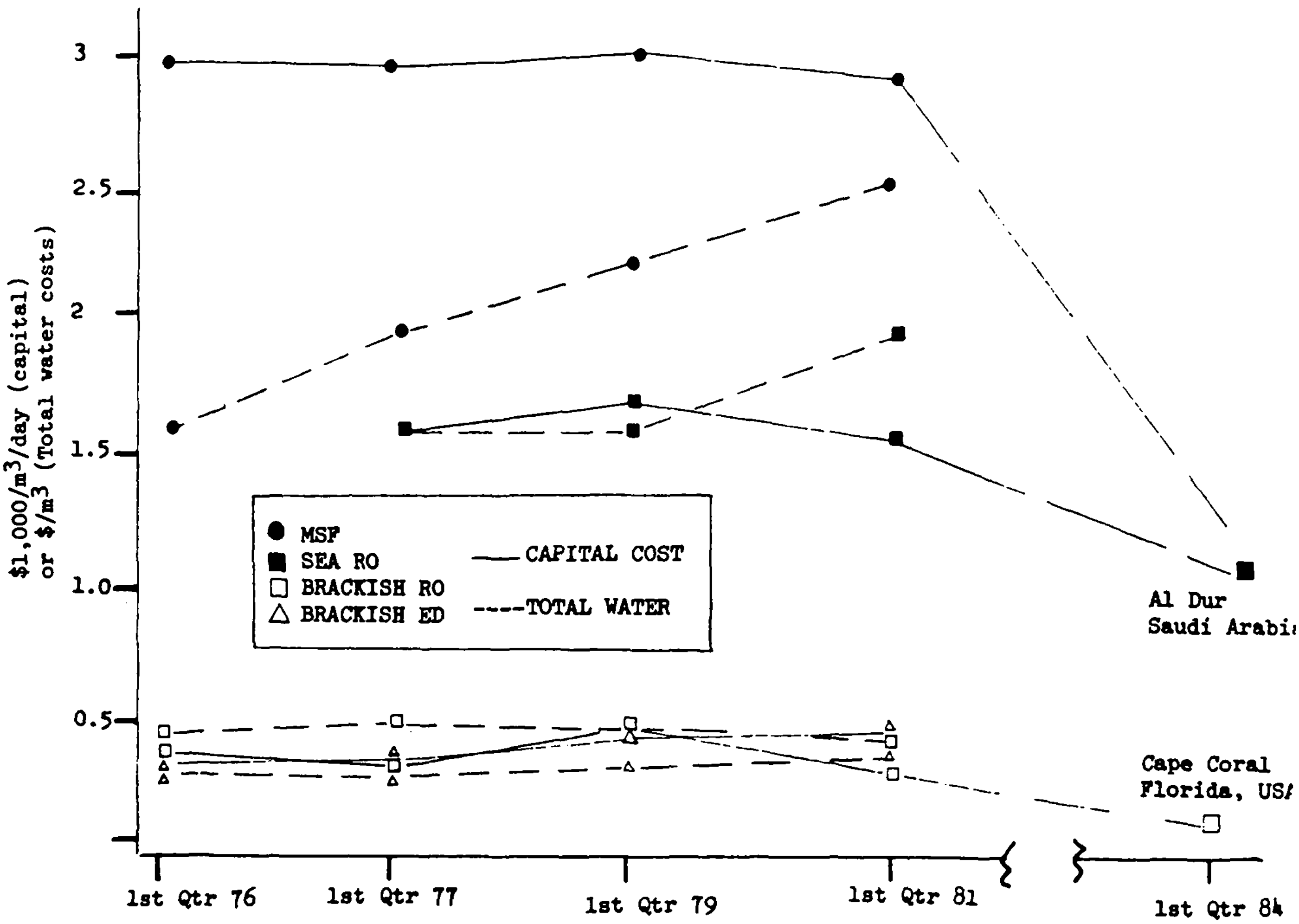


Figure 13. Trends in Capital and Total Water Costs for Desalination Facilities, 1976-1984.

Source: Oak Ridge National Laboratory Reports and Bureau of Census Gross National Product (GNP) Deflater.

Note: Costs in constant 1981 dollars.

Table 15. Costs of desalination by vapour compression

Mechanical vapour compression units, available in sizes up to about 2,500 $m^3$/day, can produce a high quality distillate at a cost only slightly higher than reverse osmosis.

Example

1,500 $m^3$/day unit at Flamanville, France, 4 effects with vapour compression.

| | |
|---|---|
| Capacity | 1,500 $m^3$/day |
| Energy consumption | 10-11 kWh/$m^3$ a/ |
| Recovery ratio | 45% |
| Equipment costs | $1,900,000 FOB ($1,275/$m^3$/day) |
| Installed costs | $2,400,000 ($1,600/$m^3$/day) |
| Total water costs, including 18 per cent fixed charges and $0.03/kWh power | $1.52/$m^3$ |

Source: F. Murat, 13 November 1984

a/Excluding feed water pumping

Table 16. Desalting plant capital costs

Capital costs include direct costs of land and equipment, and indirect costs associated with the purchasing and construction period.

(1) Direct costs

- Land
- Site development and utilities
- Equipment
- Installation
- Shipping

(2) Indirect costs

- Interest during construction
- Project management
- Working capital
- Contingency

TOTAL CAPITAL COSTS

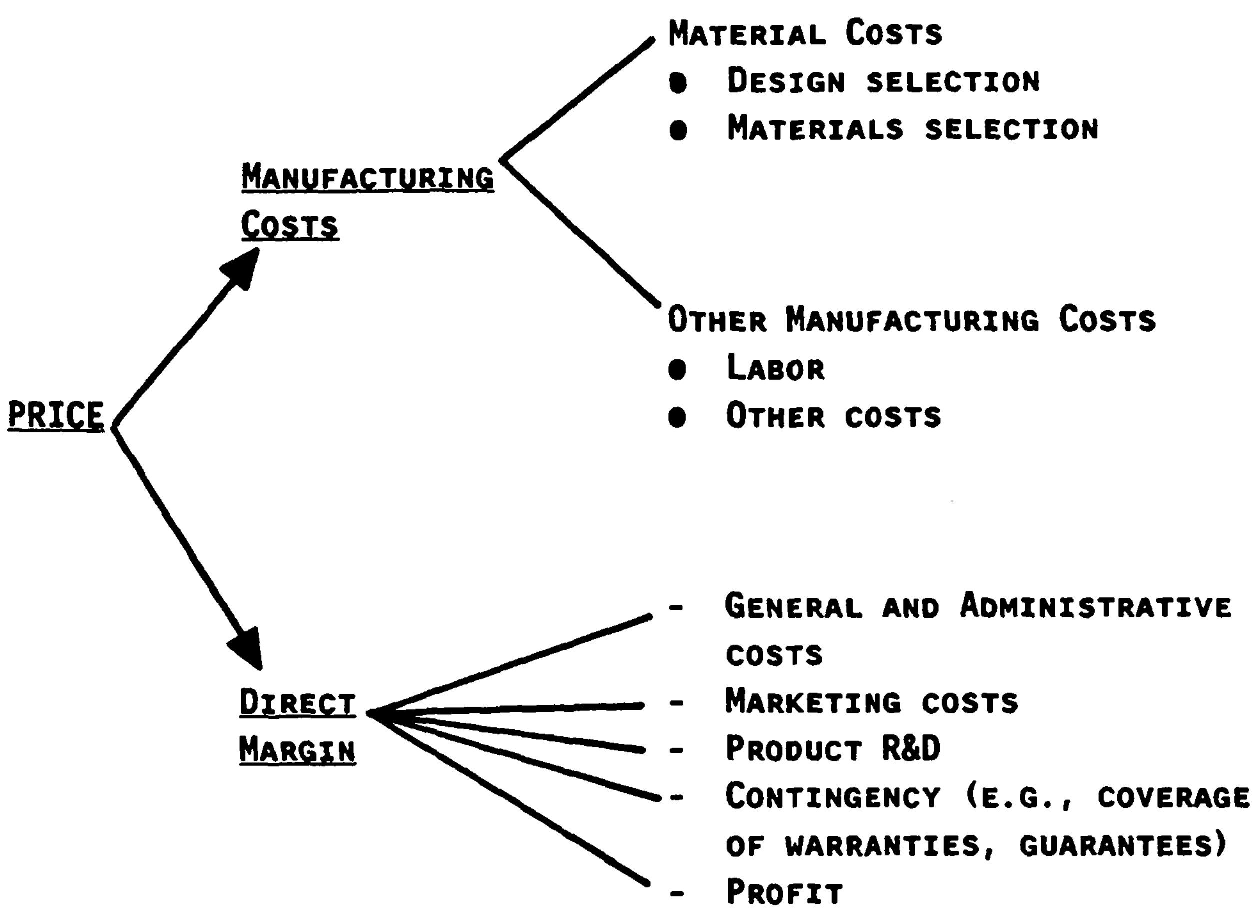


Figure 14. The components of desalination equipment costs

Notes:

1. Competitive intensity can have significant impact upon all these components. The customer should assure himself that none have been critically compromised in an effort to compete on the basis of price alone.

2. To the customer/user, capital cost of equipment is much the same as purchase price. This price, of course, is made up of many components.

Table 17. Desalting plant annual costs

Annual costs represent a combination of plant operation and maintenance costs with appropriate charges for recovery of capital.

(1) Operation and maintenance costs:

- O&M labour
- General and administration
- Energy
- Supplies
- Chemicals

(2) Capital recovery:

- Amortization charges
  (based on interest rate and recovery period)

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TOTAL ANNUAL COSTS

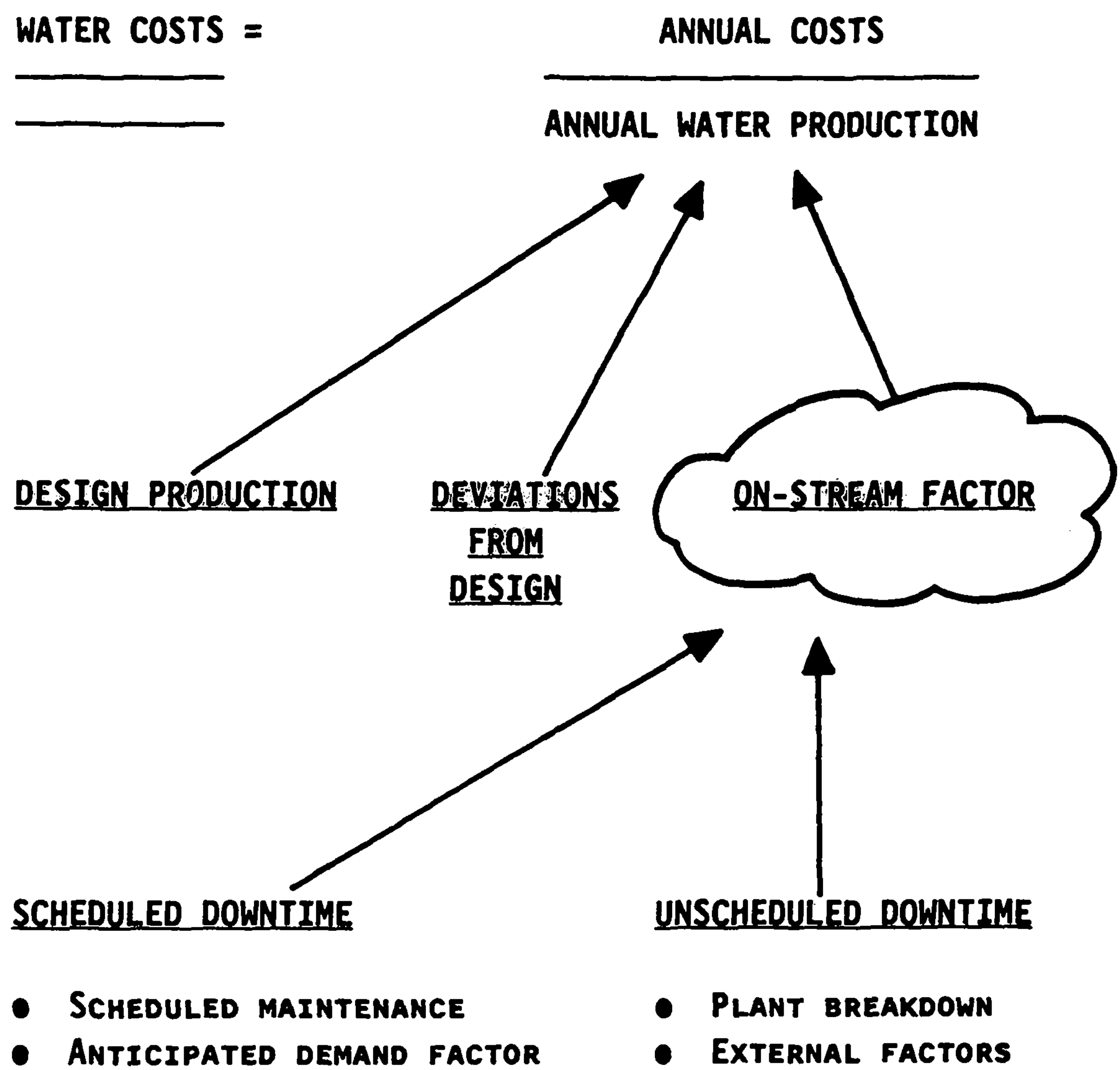


Figure 15. Factors involved in calculating desalinated water costs.

Note:

1. Water costs, usually quoted in $\$/m^3$ or \$/1,000 gal, are derived by dividing annual water costs by quantity of water produced. This quantity is itself dependent upon a number of planned and unanticipated factors.

Table 18. Typical percentage contribution of cost components to total annual costs of desalting plants

| Cost component | Type of technology and feed water | | | | |
|---|---|---|---|---|---|
| | SEA | | | BRACKISH | |
| | MSF | ME | RO | RO | ED |
| O & M Labour | 5-6% | 7% | 4% | 7% | 6% |
| General & administration | 2 | 3 | 1 | 3 | 2 |
| Energy | 22-28 | 25 | 37 | 35 | 38 |
| Supplies | 1 | 4 | 16 | 13 | 7 |
| Chemicals | 2 | 1 | 2 | 6 | 1 |
| Total O & M | 32-39 | 40 | 60 | 64 | 54 |
| Capital recovery - fixed charges | 68-61 | 60 | 40 | 36 | 46 |
| TOTAL COSTS | 100% | 100% | 100% | 100% | 100% |

Source: S.A. Reed, Desalting Seawater and Brackish Waters: 1981 Cost Update (Oak Ridge, TN, Oak Ridge National Laboratory, 1982).

Note: $0.075/kWh electric, $2.50/million BTU thermal

Table 19. Sea water RO costs as function of electricity costs ($/m$^3$)

| Cost component | Cost at $.075/kWh | % of Oper. cost | Cost at $.20/kWh | % of Oper. cost | Cost at $0.35/kWh | % of Oper. cost |
|---|---|---|---|---|---|---|
| Energy | $0.50 | 53 % | $1.32 | 75 % | $2.31 | 84 % |
| Chemicals | .06 | 6 | .06 | 3 | .06 | 2 |
| Filters | .05 | 5 | .05 | 3 | .05 | 2 |
| Other consumables | .04 | 4 | .04 | 2 | .04 | 1 |
| Labour | .10 | 11 | .10 | 6 | .10 | 4 |
| Membrane replacement | .19 | 21 | .19 | 11 | .19 | 7 |
| Total operating costs | 0.94 | 100 % | 1.76 | 100 % | 2.75 | 100 % |
| Capital costs | 0.64 | | 0.64 | | 0.64 | |
| Total water costs[a] | $1.58 | | $2.40 | | $3.39 | |

a/ Assuming 10% interest for 10 years, 330 operating days per year, $1,250 per installed m$^3$ capital costs.

Table 20. Fuel consumption in single-purpose (water production only) desalination plants

It is sometimes useful to make a direct measurement of fuel consumption at plants which are thermally or engine-driven.

Some examples:

| SYSTEM | Fuel consumption litres/$m^3$ product |
|---|---|
| Early (1940s) 2-effect distillers | ~35 |
| Small multi-stage flash (500 - 1000 $m^3$/day) | 12 - 15 |
| Multi-effect distillation | 9 - 10 |
| Vapour compression | 5 - 8 |
| Sea water reverse osmosis (without energy recovery) | 3.5 - 5 |

Table 21. Effect of recovery ratio on high pressure RO pumping energy

Example:

Paradise Island, Bahamas. A 500 $m^3/d$ sea water Reverse Osmosis plant operating at 35% recovery. High pressure pump energy requirements are 4.79 $kWh/m^3$, energy recovery is 2.25 $kWh/m^3$ for a net high pressure consumption of 2.54 $kWh/m^3$.

A rough calculation of the effect of % recovery on high pressure energy requirements indicates:

| % Recovery | Feed/ product ratio | Pump Energy ($kWh/m^3$) | Brine product ratio | Brine recovery energy ($kWh/m^3$) | Net energy ($kWh/m^3$) |
|---|---|---|---|---|---|
| 35 | 2.86 | 4.79 | 1.86 | 2.25 | 2.54 |
| 30 | 3.30 | 5.53 | 2.33 | 2.82 | 2.71 |
| 25 | 4.00 | 6.70 | 3.00 | 3.63 | 3.07 |
| 20 | 5.00 | 8.34 | 4.00 | 4.84 | 3.50 |
| 15 | 6.70 | 11.20 | 5.67 | 6.86 | 4.34 |
| 10 | 10.00 | 16.70 | 9.00 | 10.90 | 5.80 |

Notes:

1. Low % recovery will also increase the capital costs of both the high pressure pump and energy recovery system.

2. The Effect of reducing recovery ratio i.e., $\frac{\text{volume of product}}{\text{volume of feed}}$:

Advantages
a. Reduced fouling and scaling
b. Reduced pretreatment complexity

Disadvantages
a. Increased feed water throughout and pre-treatment volume
b. Increased capital and operating expenses

Table 22. Effect of recovery ratio on feed water pumping costs

Example:

Paradise Island, Bahamas. A 500 m/$^3$ sea water Reverse Osmosis plant operating at 35% recovery. Feed water is from shallow beach wells 378 m from plant site. Feed water pumping demands 0.73 kWh/$m^3$ product. Total energy consumption (with energy recovery) is 3.4 kWh/$m^3$.

A rough calculation of the effect of % recovery on feed water energy requirements shows:

| % Recovery | Feed/Product Ratio | Feed Pump Energy |
|---|---|---|
| 35 | 2.86 | 0.73 kWh/$m^3$ |
| 30 | 3.30 | 0.85 |
| 25 | 4.00 | 1.02 |
| 20 | 5.00 | 1.28 |
| 15 | 6.70 | 1.71 |
| 10 | 10.00 | 2.55 |

Table 23. Privatization as an option for plant ownership and operation

Possible Structure

1. Municipality builds facility, then sells to private entity, leases back facility.

2. Similar to 1, but private entity also operates plant, selling water/services to municipality.

3. Private entity designs, finances, builds, owns, operates plant, sells water/services to municipality.

4. Similar to 3, but with a third party investor for ownership.

Common Factors

1. Reduces need for municipality to incur up-front costs, debt.

2. May reduce need for municipality to develop appropriate work force.

3. Choice among options is a strong function of prevailing tax structure, including investment tax credit, depreciation benefits, etc.

Source: American Water Works Association (AWWA) Mainstream, February 1985.

## Conclusions

It is hoped that the preceding tables and figures will serve as a reminder that:

(1) There exists a "menu" of established technologies to serve various desalting needs

(2) Each technology is available in a broad range of capital and operating costs, dependent upon site-specific factors and prevailing economic and competitive conditions.

(3) Any single price (or cost) is the result of trade-offs made in overall design.

(4) In many cases, desalination costs will be sufficiently competitive with alternate sources of supply to warrant serious consideration of the desalination option.

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## F. Aspects of process selection for desalination

Keynote address by R. S. Silver*

### 1. Introduction

I am honoured to be invited to this Seminar, and would like to begin by expressing to the Organizing Committee of this Seminar my appreciation of that honour. It gives me very great pleasure to contribute in any way that I can to the proceedings of the United Nations, whose objectives I hold very deeply in my heart.

I have had the privilege of addressing constituent bodies of the United Nations on two previous occasions. The second occasion was in 1968 and I shall say something about it later. The first occasion was 20 years ago, when I gave a purely technical paper on desalination to a Seminar held in New York in 1965. There have been many developments in the intervening 20 years and the situation today is in some major respects very different. The following is a quotation from near the end of my 1965 paper.

"I believe that the exigencies of the future will demand that we develop distillation to its best utility, but that there will also be real scope for other processes to meet particular needs."

It has to be remembered that at that time the Multi-stage Flash Process (MSF) had only been in existence for five years as a commercial reality, for although the basic patent had been registered in 1957, the first commercial plants were the two units, each of 1 million Imperial gallons per day, which constituted the E plants at Kuwait and which began operating in 1960. Actually, exactly 25 years ago this month, I was out in Kuwait commissioning the first of these units. In 1965 it was still too soon, after only five years, to assess the impact of MSF, but now we have to recognize that for a quarter of a century it has dominated the desalination field.

The other processes referred to in my 1965 paper were freezing, reverse osmosis, and electrodialysis. Electrodialysis (ED) was then already recognized as a viable process for desalination of brackish water, but it was equally clear that it was unlikely ever to be competitive with distillation in dealing with sea water. However at that time freezing and reverse osmosis (RO) were both in their infancy, and many people expected much from development of both of them. However, in 1960 my colleague H. C. Simpson and I had already shown, in a paper to a Symposium at Wood's Hole, that reverse osmosis was much more likely than freezing to be successful (Simpson and Silver, 1960).

That brief summary of the situation as I saw it in 1965 serves as appropriate introduction to considering the choice of desalination options today.

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In choosing a desalination process for any new project, of course the major considerations must still be the technologies of the respective processes. These technologies and their differences in different processes must be understood and considered in relation to the specific project. But the situation benefits now from the large body of practical experience accumulated over the last 25 years with desalination as a source of public water supply. By far the bulk of that experience has been gained with the MSF process. For matters beyond the plant itself, however, i.e., in the distribution system, from the seawater intake and brine rejects, much of that experience will be valuable for public water supply by <u>any</u> method of desalination. Moreover, within the last 10 years, reverse osmosis membranes suitable for sea water desalination have been developed, and installations of desalinaton by RO have occurred within the last five years, so that experience is now being gathered in that field also. But, as predicted in 1960, freezing processes have not satisfactorily developed beyond the trial stage and no body of commerical experience with freezing processes exists. It has also been confirmed that electrodialysis is valuable for brackish water desalination, and a substantial amount of experience with this process can now be drawn upon.

Any process of desalination must consume energy and indeed one of the major criteria for selection of a process is always likely to be its energy consumption. I shall therefore begin my paper with a review of the energy characteristics of the alternative processes.

## 2. Energy aspects of process selection

All possible processes are subject to the laws of thermodynamics. A consequence of these laws is that there is always some connection between the energy consumption per unit product and the capital cost. Such a connection is direct and unavoidable in each process, but is different for different processes. Nonetheless, in every one it operates in the same general way, that the energy consumption can only be reduced by increasing capital cost.

The origins of this feature can be understood when we consider that any possible process, if it could be carried out in an ideal thermodynamically reversible manner, producing a very small rate of pure water product from an infinite rate of sea water feed, with negligible temperature differences for heat exchange and/or negligible pressure differences for mass transfer, would require a work energy input of only 2.8 kJ/kg (kilojoules per kilogram of product). But such a plant would have infinite size and infinite capital cost. Any real finite plant has to accept a limited feed rate of perhaps 2 or 3 times the product rate, and with finite size of heat transfer surfaces or of membranes, and finite size of mass flow passages, has to introduce temperature irreversibilities and pressure losses. There is therefore an unavoidable general trend for such losses to increase as capital cost is reduced, with an inevitable increase in energy consumption per unit product. The graphs of such variations differ as between different processes, however, and process inventive steps or design improvements can broadly be defined as devices which change the energy/capital curve in a favourable manner.

Thus, for example, prior to MSF, the distillation process was carried out either in multiple effect boiling (MEB) systems with submerged tubes or in flash systems with no more than four stages. The energy/capital curves for these systems optimized at about 800 kJ/kg, i.e., 800 kJ of thermal energy input per kilogram of product. The importance of MSF was that it immediately introduced a changed curve which optimized at about 240 kJ/kg, and that figure was in fact obtained in 1960 in the unit of 500,000 Imperial gallons per day (Igpd) which I designed for Guernsey. The Kuwait E plants were not designed for the optimum but their performance was about 400 kJ/kg, half the figure which characterized the best of submerged tube MEB or previous flash systems.

Not long after the advent of MSF, other designers realized that the MEB system could be embodied in ways other than the familiar submerged tube form, and over the past 25 years MEB has appeared in forms such as vertical tube evaporators (VTE) and horizontal tube (HT), with falling or climbing film boiling. These have the characteristic of optimizing at energy consumptions in the region of 350 kJ/kg and in that sense are now comparable to MSF, where the average installation now is at about 300 kJ/kg.

You may wonder why that is the case, since we had already obtained 240 kJ/kg with MSF 25 years ago. That is a very relevant question which I shall discuss later.

It was always clear to me that as soon as RO membranes could be found which would match the requirements of sea water, we would meet a new situation. The reason why the optimized energy consumptions for distillation are in the order of 200-300 kJ/kg is that the thermodynamic parameter in distillation is the boiling point elevation, which, for sea water, is a small quantity, only about 0.36$^{o}$C. The necessary heat transfer temperature irreversibilities are much larger than that. In contrast, the relevant thermodynamic parameter for RO is the osmotic pressure which, for sea water, is a large quantity, of the order of 30 atmospheres. The necessary pressure drop irreversibilities are much smaller than that. It follows that, provided suitable membranes can be obtained, RO will be able to operate in practice much closer to reversibility than could be hoped for from distillation.

Indeed it is reasonable to expect that work input figures for RO can be in practice as low as 25 kJ/kg. However, being a work input process, RO suffers from the inherent irreversibilities of all power production, which in good present-day practice gets an efficiency of about 33 per cent. Thus for RO we have about 75 kJ/kg for the prime fuel energy input at the generator. Once again the energy/capital general relation is seen in the RO process, where the extra cost of including a hydraulic turbine to recover energy from the pressure of the reject brine can reduce the 25 kJ/kg figure to 18 kJ/kg, with 54 kJ/kg for the prime energy.

Such is the general situation for distillation and reverse osmosis. Freezing processes suffer in comparison because they include both heat exchange and power input, so that irreversibilities of temperature arise as in distillation and also the power generation irreversibility as in RO. The net result is that the expected prime energy consumption for freezing would be about 90 kJ/kg as compared with 75 kJ/kg for RO. Other disadvantages of freezing also exist and will be referred to later. These explain why it has not developed.

Electrodialysis remains a very useful and appropriate method for brackish water desalination, but reverse osmosis is bound to offer very strong competition and may in certain circumstances be preferred. I shall include some remarks later about selection for brackish water desalination, but the main thrust of my paper is directed to the exploitation of the unlimited resource of sea water.

As will be seen in the following sections, energy consumption is not necessarily the sole factor for process selection, but it must always be a strong factor. Hence before ending this section, I must clarify further the comparative situation between distillation and reverse osmosis. By distillation here I mean thermal distillation, i.e., MSF or MEB, where the energy input to the process is directly as heat, in contrast to reverse osmosis where the energy input is directly as work. (Distillation by vapour compression, the VC process, is a separate matter which will be discussed later.)

The heat energy supply for thermal distillation does not need to be at a high temperature, and hence may be most conveniently taken as steam either from a low pressure boiler or as steam extracted from a suitable stage in expansion through a power-producing turbine. The power lost by such extraction can be replaced by the use of extra fuel in the generator, and with modern power station practice the extra amount required is equivalent to only about 40 per cent of the thermal load provided for distillation by the extracted steam. Hence by this combination method of producing power and desalination simultaneously, the prime energy required for a thermal distillation process which uses 240 kJ/kg thermal input is only 96 kJ/kg. This is the correct figure for comparison with the RO values of 75 kJ/kg or 54 kJ/kg with hydraulic recovery turbine. While there is still an energy advantage in favour of RO, it is not nearly so great as at first appears.

The above discussion suggests the first guiding selection principle. When desalination only is required, and when it cannot conveniently be coupled to use extraction steam from an existing power station, reverse osmosis will give a large saving in energy consumption compared with thermal distillation. That saving may be sufficient to swing the decision in favour of RO. On the other hand, when the project can use extracted steam from a power station, the energy consumption difference may not be decisive. There are many other aspects to be considered in each case, and it is to some such other matters thqt I now turn.

## 3. General aspects of process selection

I must begin this section by a caveat. I think I can claim that in the discussion on energy aspects, the points I have made are wholly calculable and entirely impersonal. But when it comes to more general matters, it is quite impossible to maintain the same level of impersonality, because so much of it has to come from judgement and accumulated experience. Since experience and judgement are both inevitably personal, what I now go on to say must be understood as reflecting only my own views.

Because the need for fresh water is absolute, and no other substance can replace it, I consider that reliability is the more important of all desired characteristics in a desalination process. It must rank at least as high as energy consumption in choice between processes and, I believe, higher than first capital cost. This is particularly true of large capacity plant for public water supply.

For this reason I regard it as essential that what I call - by analogy with living organisms - the morphology of the process should be as simple as possible, i.e., should have very few distinguishable main operating elements in its construction. The ideal process should approach as near as possible to conventional catchment water supply where the essential elements consist only of envelopes and connecting passages to contain the water and allow treatment of it, and pumps to convey it through the envelopes and passages. Evidently all these have to be present also for water supply by desalination, but what has to be added are whatever elements execute the function of separating fresh water from the saline feed. These elements should be as simple and uniform as possible, and as dependable as possible.

I think the validity of this view is illustrated forcibly by the history of freezing processes. In all of these, the separation required several elements of diverse nature, including water/brine heat exchangers for temperature recovery, refrigerant materials in refrigerant circuits to freeze feed or brine to ice, washers to separate the salt from the pure ice crystals, and remelters. At least all these diverse functions were required, even when some could be carried out simultaneously in one specially designed device. The practical difficulties in obtaining reliable operation in such diversity were revealed in all the attempts to develop freezing processes and they have effectively vanished from the large capacity desalination scene. It seems also unlikely that they can compete successfully in the small capacity market now that reverse osmosis is available.

This theme of the advantage of morphological simplicity also to my mind explains the continuing ascendancy of MSF distillation over MEB distillation despite the fact mentioned in section 2 that MEB in its modern embodiments can match MSF in energy consumption. The point here is that MSF requires only one species of heat exchanger. The heat input section, and every stage in the recovery and rejection sections, perform only the same kind of heat transfer function, vapour condensing outside tubes through which brine is pumped at positively determined rates. In contrast, MEB cannot function economically with heat exchange equipment devoted to boiling alone. To get energy consumption comparable with MSF, there has to be included in any MEB circuit other heat exchange equipment designed for preheating the feed. Thus a diversity of function and structure is necessarily present in MEB which is absent in MSF. Indeed MEB in practice is actually a mixture of flashing and boiling operation. In the usual temperature range anything from 15 per cent to 20 per cent of the product may be produced by flashing. I have shown (Silver, 1971) that MSF and MEB can be regarded as the two ends of a possible continuum of distillation processes where the variable is the quantity of circulated brine. Obviously the minimum circulating quantity is the feed, and if you use only that as in MEB, you have to include boiling to get the desired output, since you get only 15 to 20 per cent by flashing. Increase the circulation gradually by recirculation and you produce more by flashing and need less boiling. Continue this trend and you reach the MSF process where all the product is obtained by flashing and you need no boiling. It does seem inherently more logical to go to the MSF end of the continuum which can eliminate boiling, since the MEB end cannot eliminate flashing. The boiling heat transfer regime is inherently more variable than the forced convection regime which alone is experienced by brine in MSF, and the scale formation behaviour is consequently less predictable in MEB, particularly with film boiling.

I believe this feature of a uniform heat exchanger regime throughout the whole plant, a regime of forced convection controllable by the positive action of pumped flow, is a major asset of the MSF process in respect of dependability as compared with any embodiment of MEB.

For at least the last 20 years designers of MEB processes have been challenging MSF in the market but without much success so far. Since the energy consumption can be comparable and since MSF has the apparent disadvantage of requiring large recirculation pumps, there have to be some good reasons for its continuing success. I believe the explanation lies in that asset of reliability, arising from the simplicity, uniformity, and controllability of the heat transfer regime as discussed above.

I therefore conclude that MSF is the best form of thermal distillatiion process for large capacity public water supply by desalination.

Turning now to reverse osmosis, the first thing to note in this respect is that with a given membrane, RO conforms to the same prescription of general desirable characteristics. As in MSF the morphology is simple and uniform throughout. In each case, MSF and RO, all we have are envelopes and passages to contain and guide the flows, and a single uniform separation function. In MSF that function is driven through the uniform "membrane" of heat transfer tubing. In RO that function is driven by mass transfer through a selectively permeable membrane. From that point of view, the processes are similar in form to an extent which is quite surprising, considering their respective starting points of distillation and osmosis. I believe that that similarity reinforces the view that they must be regarded as the main contenders for major desalination projects in the future. How then are we to choose between them?

The first point is of course that already decided in section 2. For small capacity, or for large capacity desalination which cannot conveniently be linked with extracted steam from a power plant, the energy advantage of RO is probably sufficient to indicate RO as preferable, provided reasonable reliability is obtained. But for large capacity which can be combined with the use of extracted steam from power plant, the energy margin in favour of RO is not sufficient to give immediate preference. The capital cost will certainly have to be examined closely, and the vexing question of reliability will require much more careful consideration. This is where we come up against the difficulty of judging between, in the words of the old proverb, "the devil we know and the devil we don't know". We have a quarter of a century of experience of large capacity MSF. We have as yet none of RO at comparable capacity and only two or three years of any capacity on sea water. Are there any guidelines which we can follow, particularly with respect to reliability? In the next section I make some attempt to deal with that question.

## 4. Important differences between MSF and RO properties

In section 2 and 3 it has been shown, from the aspects of energy consumption and general morphological simplicity, that the choice for large capacity sea water desalination narrows down to MSF and RO. These two processes alone have the common characteristic of requiring only retaining and controlling envelopes, passages, and pumps, with only one form of separation function in each, forced convection heat transfer through a metal "membrane" in MSF and forced mass transfer through a semi-permeable plastic membrane in RO. There are of course differences within that general similarity and these differences may affect the expectation of reliable performance.

The basic difference is that the materials used in MSF have very little effect on the essentials of the process, whereas in RO the very possibility of the process occurring depends precisely on the availability of a specific material. The relative materials concerned are the heat transfer tubing in MSF and the membrane material in RO. The envelopes, passages, and pumps may be the same or dfferent material in each process, but they are irrelevant to the present point. In the MSF heat transfer process the overall coefficient is only very slightly affected by the thermal conductivity of the material and the performance would be practically the same for any metal. In contrast the salt rejection and the water flux in RO are so crucially dependent on specific properties of the membrane that unless the material is precisely correct for the water condition, the process performance can be completely unsatisfactory.

A second important difference between the two processes is that the heat transfer behaviour in MSF - excluding for the moment questions of scale formation, which I shall discuss later - is quite unaffected by trace substances in the water, as such variations do not appreciably affect the Prandtl and Nusselt numbers which determine the transfer process. But the behaviour of RO membranes can be very susceptible to trace substances in the water, and performance can be very variable.

The simultaneous existence of these two differences implies that RO is subject to much greater risk of performance failure than MSF unless the quality control in membrane manufacture, maintenance of that quality in storage, shipment, and installation, are extremely good; also the operation must include precise treatment of the sea water intake to give effectively a similarly high level of quality control for the brine on which the membrane is to operate.

Now of course manufacturers of membranes and suppliers of RO equipment are fully alive to these risks and no doubt will exert the necessary control and implement appropriate practices on site during erection and operation. Water treatment to control scale formation in MSF is familiar practice - but it has a long history of development. I am quite sure that risks of performance failures with mismatched membranes and brine are very much greater than risks of scale formation in modern MSF plant, but I am equally sure that in time these risks will be overcome as RO develops. The point I must make, however, is that the probability of malperformance is quite high, and some quite serious failures may occur in the near future until the specificity of RO membranes is better understood than it is at present. As I urged last year at the Water Supply Improvement Association Conference in Florida, there is a real need for technologists in RO to develop a system of engineering concepts for the RO process analogous to those which are well established in the distillation field. Such a system is essential for the intercomparison of experimental data in the laboratory and of operational data from the field.

Provided that is done, I think we may be certain that RO will very quickly replace MSF for single purpose plants, and will also secure a substantial place in the market of dual purpose plants. I do not think it will replace MSF entirely in that field, because there will always be situations where a high purity of water is preferable. I must conclude this section by explaining that remark.

One difference between the two processes which I have not yet mentioned is vital here. The nature of the RO process is such that it cannot, in a single membrane flux, produce a product water, from a sea water intake, of less than about 200 parts per million (ppm) of total dissolved solids (TDS). I think that characteristic will remain even in possible future development of membranes. If I am correct in that belief the fact that MSF can quite easily guarantee less than 50 ppm in the product water from sea water desalination gives it an advantage which can be decisive in certain cases. First, such a product can be blended with brackish water to give a higher total rate than is obtainable by mixing RO output with brackish water. Second, where high purity water is needed for industrial processes the MSF output incurs much less demineralization cost than does the RO product. Moreover, it is quite frequent practice to include in the MSF plant a section which, at very little extra cost, can produce part of the output with a guarantee of less than 1 ppm, which is already suitable for most industrial requirements.

There is, however, one disadvantage of RO at present, which I believe may be overcome in future membranes. At present the recovery possible from sea water in RO is about 30 per cent. This means a sea-water feed ratio of over 3, in contrast to abvout 2 for MSF. (These feed ratios refer to standard specification sea water, and both must be increased for sea water of higher concentrations.) Thus, the sea-water intake design is always considerably larger and more expensive for RO than for MSF at present. It is possible that this disadvantage may be reduced in the future, since membranes capable of greater recovery may be developed.

I think that completes the account of the main operational differences between MSF and RO in their present state of development. Clearly MSF is much more developed along its possibilities than is RO and greater development may be expected from the latter. In the next section I shall show, by surveying what has actually occurred in MSF over the last 25 years, that other developments of this process are still possible.

## 5. Development limitations and possibilities in MSF

In my view, while there has been much development in MSF since its inception, there could have been more, and what has occurred could have been beneficially different. Certain limitations on development have occurred in its history, and I think it is worthwhile discussing these, because some of them may be equally applicable in restricting development of RO.

The first influence, a major one, is that of restricting the energy consumption to values poorer than are technically possible. Such restriction arises directly from interest rates charged on capital.

It should be obvious that when in the mid-1970s rapid increases in fuel prices occurred, desalination should have moved to the better energy consumption designs which were technically feasible and already demonstrated. That would no doubt have occurred had interest rates not been increased also. The sad fact is that the benefit of technological research and development which advances efficiency, and which has cost not only the money invested on such research but also the brains and best endeavours of those engaged in it, can be wiped out at a stroke by the entirely non-technological action of financing policies which increase interest rates.

In section 2 I mentioned that MSF achieved 240 kJ/kg immediately in 1960, but yet the average in use today is poorer at about 300 kJ/kg. Higher interest rates have kept the optimum position at lower capital investment and higher energy consumption. Thus not only is more of the world energy stock consumed needlessly, but the development of desalination as a whole is restricted to areas with cheaper energy. That direct interest factor will clearly operate on RO as well as on MSF and indeed may hinder the relative development of RO with hydraulic turbine energy recovery.

However, there has been a rather more subtle technological reason which I think has unduly limited the possible development of MSF. On this point I have to say that I base my argument on my own design philosophy, which of course many designers do not share. The essential concept introduced by MSF was to use a much larger number of stages than was thermodynamically necessary for a particular designed energy consumption. In my basic patent I stated that the number of stages must be greater than twice the performance ratio. In the Kuwait E plants the value was just over 3 times and in Guernsey about 4 times. The point of the large number of stages relative to the performance ratio was to get higher mean temperature difference for heat exchange for a given performance and so reduce the amount of heat transfer surface required. To do that means having more stages, and so means that heat transfer tube material is saved by increasing the amount of stage wall material. The assumption behind the design principle is that heat transfer tube material is much more expensive than stage wall material. Hence, the extent to which the actual number of stages can be economically increased depends on the relative cost of heat transfer tubes and of stage walls.

In my design thinking I contrasted aluminium-bronze (Al-Br) or copper nickel (Cu-Ni) heat transfer tubing with mild steel walls, where the cost difference is great. However, as the field developed, that principle was not fully appreciated by those who put forward arguments for corrosion-resistant materials for the walls, or for coatings or claddings on the walls. These reduced the difference in relative cost of tubing and walls, and so led to lower stage numbers and poorer energy performance.

The question of corrosion-resistant walls is complicated by various factors, including the understandable marketing zeal of manufacturers of corrosion-resistant materials and of claddings and protective coatings. There was for a time also a proper technological factor at work, when in an effort to raise the top temperature of the flash range, the acid treatment method of scale prevention was urged. The stage walls were therefore at considerable risk unless protected against corrosion. Fortunately it has now been possible to extend the flash range as far as is thermodynamically desirable, with the use of new scale control additives instead of acid. The acid treatment method, which had caused frequent operational corrosion difficulties despite supposed protective measures, is hardly likely to be used in future. I believe there can therefore be improvements in MSF performance at lower cost by applying more rigorously my original philosophy of using the cheaper stage wall material with the scale control additives now available.

Most corrosive actions have some electrical potential concomitants. Coatings inevitably get scratches or pin holes and thus corrosion occurs locally and intensely and can lead to failure locally. Claddings can part in the course of service and interstitial corrosion can occur quite seriously. Uncoated mild steel surface corrodes almost uniformly all over and is much less likely to lead to local failure. I consider therefore that coatings and claddings are sources of trouble, and that the best practical corrosion protection for mild steel walls in desalination use is an extra two millimetres thickness.

I should remark here that no one has yet accepted my views on this matter in full. The nearest was in the very first installation, the E plants in Kuwait, where only an internal epoxy resin protection was given to the mild steel fabric. I think that early on some of that coating came off in bits and gave slight trouble in the pumps, and the risk of this is another source of objection to coatings. However I understand that both the E plants continued satisfactorily in operation up to 1980, and were closed down only to make way for new developments. Thus, that very first MSF design achieved a 20 year life. I think it would be a useful contribution if some report could be published giving its detailed history over that period.

Having mentioned that fairly successful matter, I feel I ought also to mention one less successful. I carried the philosophy of lower cost structural materials even further in the Guernsey 40 stage plant also commissioned in 1960 by making the tube plates also of mild steel, although chromium plated. It cannot be said whether or not that would have been successful, because the frequency of use of the plant turned out to be low, for quite extraneous reasons. The result was that it lay idle for months between short periods of operation, and general corrosion of the steel work was extremely bad, naturally enough with damp surfaces left open to the air. In these circumstances the tube plates were the only steel parts which did not corrode.

The Guernsey plant had another unique feature which, so far as I know, has never been tried in any other. In it I provided a separate set of tubes in the tubeplates to take the feed parallel to the recirculation, so that mixing occurred at the top temperature instead of the bottom as in Kuwait E and every other plant since. This was intended to be better for deaeration and I believe would have been. I rather regret that it has not been tried again. In modern plants of course very sophisticated deaeration and degassing is now included, some excessively in my opinion and adding needlessly to cost.

Another trend which has restricted the improvement of MSF performance has been the drive to what I regard as unduly large unit capacities. The desire to get unit capacities of 5 million Igpd and beyond demands the development of large circulating pumps with difficult siting to get adequate suction head. More important, in cross-tube design, it requires, unless the chamber construction becomes rather complicated, a tube-length which is longer than thermodynamically desirable and so drives the energy consumption up. The through-tube design (frequently called long-tube) is free of that objection since the tube length is independent of the flash stream width. But it has other defects. On balance I think that cross-tube design and a unit size of 2.5 million Igpd is an optimum specification. Installations of larger total capacity can still get much reduced capital cost from the bulk buying of multiple units of that size, and have greater flexiibility and reliability in operation.

It may be worth mentioning at this point that large capacity installations of RO will also have to consist of multiple units, each unit perhaps smaller than the MSF size I have suggested above.

To sum up, I suggest that a more stringent attention to the basic intention of MSF design with cheaper wall materials and the enhanced scale control additives now available, and a wiser policy in financing the capital, could lead quite rapidly to MSF energy rates down to 200 kJ/kg with reliability, and therefore to about 80 kJ/kg prime energy consumption in dual purpose plant.

## 6. Brief review of other aspects

### (a) Small capacity units

While large capacity desalination for public water supply is the main interest, there must also arise in developing nations the need for smaller capacity plants suitable for water supply to institutional buildings, hotels, and the like. Such installations will almost always be single-purpose plants, i.e., not suitable for combination with power generation. With RO now definitely in existence, it is therefore unlikely that any such institutional plant will in the future use thermal distillation, since it would mean supplying boiler plant also. But it is in this field that vapour compression distillation may be an effective competitor to RO despite its higher energy consumption, because it can give the high water purity guarantee characteristic of distillation.

Away from sea-shore sites, institutional plants having brackish water as feed will be generally served by either electrodialysis or by RO, depending greatly on the particular ions which may be present in the feed water. Again, however, if high purity product is needed for special purposes, vapour compression distillation will be appropriate.

### (b) Relation of desalination to water reuse

The organizers of this Seminar have quite properly scheduled the discussion of water reuse separately from desalination, because the subjects are very distinct. However there is one aspect in which the one may impinge on the other, and to which I should make reference.

The contaminants which must be removed from water which is being reused will normally include a far wider range of organic materials than are common in sea water and almost certainly some of these will be volatile in the same temperature range as water. In that case, distillation is automatically ruled out, for such volatiles will merely distill over and recondense in the product. Equally, electrodialysis will be limited since many of the organic impurities will not ionize. The technology required will be mainly advances in classical water treatment of coagulation, flocculation, and filtration, but there will also be scope for reverse osmosis membranes developed specifically for re-use impurities and not identical with those used for desalination. However, the existence of this application for the RO process should assist the development of RO desalination indirectly. The reason can be understood with reference to a corresponding situation in MSF. The cost of heat transfer tubing in MSF would be much higher if there did not exist a huge market for heat transfer tubing in applications other than in desalination. As it is, desalinaton is only a fraction of the total market for heat transfer tubing. Thus the development of RO for effluent treatment and for water reuse, by extending the market for RO engineering, pumps, and auxiliaries will similarly help RO in desalination. Note, however, that membrane sales will not benefit directly in the same way as heat transfer tube sales, because the membranes will be differently constituted for the different uses.

## Conclusion

I hope you will allow me to conclude this paper now on a more general note. This Seminar is concerned with non-conventional water resources in developing countries. Desalination is included as one of such possibilities - but in certain developing countries it has probably become the conventional water resource. Much of its application in other developing countries is likely to depend on the transmission of information on and experience of desalination in practice from those countries in which it is now almost conventional, to those other developing countries where it can also be useful. The passage of such information and experience must be very much in the mind and heart of the United Nations.

I mentioned at the start of the talk that I had spoken on two previous occasions to constituent bodies of the United Nations. But I only mentioned then the first occasion, a technical paper to the New York Seminar on desalination in 1965. I hope you will forgive me if I conclude my paper today by referring to the second occasion, which was in 1968, in Paris, at the General Conference of the United Nations Educational, Scientific and Cultural Organization (UNESCO) that year. I had then the great honour of being awarded the UNESCO prize for Science. I said then, in my acceptance reply speech, that the message of all the advances in technology, of which desalination is only a recent and minor example, is a very important message, but a very simple one. It is simply that, technologically speaking, it is now within our power to ensure that there is neither starvation nor other material suffering anywhere in the world. But to make that possibility become actuality, technology is not enough. It also needs the will of all nations to work together, to co-operate. There is no choice of process in this matter, there is only the choice between international friendship or disaster.

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## Appendix. Comments on seminar discussions

This appendix to my paper gives an overview of the discussions at the seminar, which dealt with desalination technology, and with experience in desalination operation, respectively. The presentations on technology gave a reasonably accurate picture of the state of technology as it exists today.

Using my prepared paper as a checklist, there was no wide difference between what was presented and what I had anticipated, except in one respect, namely the emphasis in the paper by D. Hoffman on low-temperature MEB distillation. Of course, it is attractive in principle to work at temperatures below those at which scale will form, and admittedly it is not possible to do so in MSF because the recirculation ratio would become excessive. However, we now have long experience with scale control additives, which operate very effectively over the temperature range required for MSF. Hence, unless low-temperature MEB distillation offers something else besides freedom from scale, it will be subject to the same criticism as given in my paper.

Mr. Hoffman correctly pointed out that the use of backward feed removes the preheaters, but it does so only by the alternative complication of intermediate pumps and accompanying level controls. I should also say something more about vapour compression than I did in my paper, because developments in this process were mentioned both by Mr. Lucas and Mr. Hoffman. Each referred to vapour compression by steam jet and by mechanical compressor. For the former, multiple effect operation is essential to get satisfactory energy economy, since the steam jet latent heat has to be recovered as much as possible.

However, the authors each advocated multiple effect operation of mechanical vapour compression. This is not directly necessary for energy economy, since the vapour compression process is thermodynamically a heat pump process, and the specific energy input for a given compressor efficiency, is governed entirely by the temperature differential. The use of multiple effect in this case is dictated by the size of compressor needed to handle the volume of vapour. Thus, in a four-effect plant, approximately one quarter of the product only is handled by the compressor, but is compressed approximately up four times the temperature difference in each effect.

If a large enough compressor could be designed, the whole product vapour need only be compressed up the single effect temperature difference, giving approximately the same overall specific energy consumption. That analysis reveals the limitaton of the vapour compression process to smaller capacity plant as discussed in my paper.

The power energy consumption figures given by both Lucas and by Hoffman were about equal, at approximately 40 kJ/kg. That confirms my view that RO at 25 kJ/kg, even without a recovery turbine, has a good energy margin on vapour compression. Thus I hold to the view that in small capacity single purpose plants, RO is likely to be preferred except when high purity water is required. Vapour compression will be the better choice in those circumstances.

Apart from these few points, the sessions on technology and experience were in general accord with the situation expressed in my paper. Dr. Birkett in his address expressed the position very dramatically - MSF and RO "in mortal combat", and MED and vapour compression..."Heroically refusing to lie down". Shorn of the dramatics, this does reflect the position I described for sea water, with the realization, however, that for dual purpose large capacity plants MSF will in general be preferred for some time to come. The great experience now accumulated with MSF is not yet matched by RO.

It was recognized frankly in some of the presentations that the warnings I gave in my paper about the risks arising from the specific character of membranes are well founded. In regard to desalination of brackish water it was confirmed that the choice lies between EDR (electrodialysis with reversal), or RO. A major point brought out in the discussions here came from the paper by P. Culler, and concerned the problem of brine disposal for desalination of brackish water at inland sites. Although this was raised by Culler in a paper directed to RO, the problem exists for desalination of brackish water inland by any process. There is no easy solution to it, and cannot be any general one. The disposal of brine from brackish water desalination will be as specific to the location as is the brackish water source itself.

A summary of the overall findings in respect of process choice for sea water is as follows. For high purity water for industrial use, only distillation is acceptable. For capacities less than 4,000 $m^3$/day this will probably be most effectively obtained by vapour compression. Above that range MSF will be preferable. For potable and general purpose water, reverse osmosis will be the preferred process when the project is a separate desalination [illegible]alone, using power available from an existing source. When the project can couple the desalination plant to a steam power generation plant, or use a source of waste heat, distillation will, in general, be preferable to reverse osmosis. In such cases the choice of distillation between VC and MSF will be based on the capacity criterion as above.

In regard to the detail of individual processes, scale control in MSF will in future be by the proven additives or their successors, and acid scale control is unlikely to be used again. In any case, there is no thermodynamic advantage in increasing the top temperature range of MSF beyond that for which satisfactory scale control is now well established.

In RO there is still little experience of the variable specificity of membranes and very good quality control of both membrane and water treatment must be established. Without that, some serious failures of RO projects may occur.

I would like also to direct attention to those parts of my paper which I omitted from my verbal presentation, which concern the materials of construction. The points made there did not come up in the discussions, but I believe them to be important. Apart from the direct relative cheapness of mild steel compared with alloys, the simplicity of welding repairs where necessary will be relevant in developing countries.

Finally I should record my appeal to the World Bank representative to look carefully at the point made in my paper in regard to the effect of interest rates.

## III. TRANSPORTATION OF WATER BY TANKER

### A. Innovative approaches to transportation of water by tanker

by Trygve A. Meyer*

#### Introduction

The United Nations International Drinking Water Supply and Sanitation Decade offers some magnificent overall objectives in providing access to water for all by the year 1990. About half-way through the decade, meaningful and measurable results could be produced, but too many people in the world are still underserved for their basic water needs. Water availability of the required standard is rapidly diminishing in many densely populated areas in the world, with great challenges ahead in the search for innovative sources of water.

Parallel with the United Nations plans to provide safe water for all by 1990, comes the accelerated water supply projects for the rich Middle Eastern oil producing countries. Other developing countries are poor both in oil and water, while some industrial oil-importing countries are dependent on oil importation, but on the other hand, they have an abundance of good quality water available for exports.

The International Association of Independent Tanker Owners (Intertanko), a non-profit organization, represents tanker owners situated in 32 maritime countries. Among other important topics, Intertanko has, since 1978, promoted the concept of fresh water transportation in oil tankers. Water transportation concepts are gaining momentum, and in its campaigning Intertanko is communicating with a broad sector of the shipping industry, consultants and Governmental bodies situated in Middle Eastern Gulf countries. A main breakthrough for the tanker transportation concepts occurred in May 1983 when the United Nations International Maritime Organization (IMO) in London held a two day seminar on "International Fresh Water Tanker Ballasting".

#### 1. World tanker fleet

##### (a) Main oil tanker routes

Tankers which have unloaded their cargo have to take on ballast to ensure stability during the return journey. At present sea water is usually taken on for this purpose into cargo tanks or separate clean ballast tanks. The supply of 25 - 50 per cent of the quantity of oil exported in the form of fresh water as ballast in the tankers on the return journey is feasible, with no extra fuel costs. The potential also exists to carry full loads of fresh water as return cargoes.

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Fresh water backhaul transportation, in combination with existing oil export trade routes from the Middle East and North Africa provides great potential for fresh water supply to arid oil exporting countries, or for discharging in developing countries situated along tanker routes lacking water. By far the largest part of the oil export from these countries is transported along principal trading routes to Western Europe, North America (including the Caribbean) and Southeast Asia.

Total oil exports along the principal tanker routes amount to about 500 million tons annually, of which about 50 per cent are transported by very large tankers in excess of 200,000 dead weight tons (dwt) from the Middle East Gulf.

(b) Tanker availability

The world tanker fleet and, in particular, the fleet of very large and ultra-large crude oil carriers (VL/ULCCs) of 200,000 dead weight tons and above, grew dramatically in the early 1970s because of the trend towards large tanker size precipitated by the Suez Canal closure in 1976. Between 1971 and 1975 the large tanker fleet burgeoned from 49 to 133 million dead weight tons. Reduced tonnage demand after the 1973-74 and 1979 oil price rises, aligned with the over-expansion of fleet size, produced a massive tanker tonnage surplus in the mid-1970s. This has persisted despite high scrappage and virtually no new building activity since 1979.

Severe overtonnage has meant that large tankers have traded at an almost constant loss over the past decade and many vessels are unlikely to survive to see profitable trading conditions returned. At the moment, the effective tanker tonnage surplus represents some 37 per cent totalling about 95 million dwt. The decline in the laid-up tonnage is partly a result of demolition of tankers and partly of the owners' search for alternative profitable trading opportunities. The significant tanker surplus in all size groups ranges from about one-third of the fleet in the case of smaller tankers to more than half of the supertankers. As many as half of the 500 supertankers are estimated as surplus tonnage.

In coming years the prospects for the aging supertanker fleet is dim. Premature scrapping of a great portion of the remaining units may result in the absence of profitable oil trading opportunities or alternative tanker uses in the years to come.

(c) Environmental laws and technological improvements for cleaner tankers

The increased value of oil since 1973 and environmental restrictions on ballast water discharges, have led to much improved tanker cleaning technologies and operations. The prevention of oil pollution from ships is dealt with by the International Maritime Organization (IMO) and the governing legislation is covered in the International Convention for the Prevention of Pollution from Ships, known as MARPOL 73/78. This convention became effective internationally as from 2 October 1983. New requirements include crude oil washings of cargo tanks after discharging and segregated ballast tanks for new tankers. This means that the cargo tanks on the ballast legs will be much cleaner for the transportation of fresh water. The upgrading of existing tankers to meet new operational and equipment standards is costly and may contribute to premature demolition of tankers rendered out of standard for the safe carriage of oil.

2. Infrastructure for the loading, discharge and delivery of fresh water

(a) Innovative modes of fresh water transportation

The approach to shipping water on oil tankers may be very attractive and may be economically feasible. Such modes of water transport include:

(i) Backhauling of fresh water as ballast to oil-producing countries in tankers whose chief purpose is to carry oil.

(ii) Carriage of fresh water in clean segregated ballast tanks for domestic uses in arid oil-exporting countries.

(iii) A shuttle service provided by tankers that will only be used for transporting fresh water.

(iv) Water harvesting in the Antarctic.

The introduction of fresh water backhauling services implies institutionalization of a secondary trade (water) in a well established trade (oil) organized under its own logistics and rules.

A regular shuttle service between the export and import ports could be set up and run all year long, independently of fluctuations in the tanker freight market. Another advantage is that the water would be shipped in clean but less sophisticated tankers, simple to maintain and operate.

To implement a fresh-water ballasting system when the water source is available at the loading port is fairly simple as the installations already exist to some extent. Almost any tanker returning to the Middle East could be used, even the smaller product tankers. New techniques or different ways of operating the vessel and the equipment are not necessary. It should be noted, however, that any quantities of water in excess of that required for ballast soon become more expensive and some of the shipping companies' flexibility would be lost. Where the point of loading the water and delivering the water is different from the point of loading or discharging oil, the voyage would last longer and extra transport costs for deviations would be incurred.

(b) Water as global resource

In the years to come, more and more attention has to be given to secure a reliable supply of good water. At the 21st International Horticultural Congress, 1982, Professor Sylvan H. Wittwer stated: "Fresh water sources are critical. Crop irrigation for agriculture in the United States now consumes 80 - 85 per cent of the total fresh water resources withdrawn from lakes, streams, and ground waters. This is a problem for many other places of the world. There will be increasing competition for these resources to meet future recreational needs, industrial uses and for the extraction of energy and other consumptive uses by people. A major water crisis is projected for the United States within the next decade."

Societies are confronted with the challenge, on the one hand, to reduce or eliminate the effects of the world's water deficiency and, on the other hand, to regulate the excess of water so that we can make use of the potentials that are lost. In many areas of the world with low surface water run-off, the available underlying ground water is generally of poor quality. As depletion occurs and additional minerals are added by percolation through mineralized soils, the quality of both surface and ground water deteriorates. Mining or over-extraction of ground water in many locations has also resulted in sea-water intrusion so that the water is rendered brackish.

Intertanko has attempted to survey available and planned water port facilities around the world. The list of available water is far from complete, as the survey has only been concentrated on excellent water quality sources.

Water that can be made available for export stems from hydro-electric power stations, lakes and river esruaries. In Northern Europe water is available from Norway, Scotland, Ireland, Federal Republic of Germany and the Netherlands. In addition, ample supplies are available in some European Mediterranean ports such as Fos and Lavera. The province of Galicia in Northern Spain also has large quantities of river water available for export. In Asia, Yakushima Island (Japan) and the Philippines can supply water for oil tankers returning to the Middle East for loading oil. In the Western Hemisphere water redundancy exists on the Pacific coast of Canada, as well as in river estuaries on the United States East Coast. Finally, there exists a potential for water harvesting from icebergs and islands in the Antarctic.

Water in large quantities can be made available for shipments on short notice from Norway, the United Kingdom, the Netherlands, Spain and from the South of France. Facilities for loading water at other locations need to be established.

(c) Characteristic properties of oil/water mixture

International marine pollution control legislation now requires improved tank cleaning methods by the washing of tanks with crude oil in discharge ports, before taking on departure ballast. This means that the cargo tanks on the ballast leg will be much cleaner for the transport of water. The normal amount of crude oil remaining in tanks after unloading is 0.5 - 0.7 per cent. With crude oil washing, this figure is reduced to 0.1 to 0.2 per cent. This means that the oil content of water in ballast tanks, after an efficient crude oil washing, can be less than 200 ppm. After a tank bottom water rinse, as the standard pollution control convention requirements, the oil contents in the fully water-loaded cargo tanks can be less than 15 ppm. Still owners have the option to modify existing tankers to operate with dedicated clean ballast tanks which will not contain oil cargoes on the loaded leg.

The oil left over in the tanks after discharging and water loaded for the ballast trip will not mix, but form two layers of liquid which are relatively easy to separate. Components of the oil may nevertheless pass into the water and form aromatic compounds. A large number of experiments have shown that, apart from the top layer of about 1 - 2 feet of each tank, the ballast water in the rest of the tanks after a fortnight's journey show that the oil content in the water can be less than 5 ppm. Such levels of oil contaminants in water used for irrigaton seems to have minor adverse effects on the soil, plant growth and crops.

Under new international marine pollution control legislation, special vulnerable areas such as the Mediterranean Sea and the Middle East Gulf have been declared specially protected areas where no discharging of oily waste from tankers can take place. Deballasting facilities will be required at oil exporting terminals in these regons. When provided, such facilities may be dual purpose, as clean fresh water ballast can be pumped ashore from the ship and become an integral part of the water supply system.

(d) The purification process

Actual measurement of available ballast water in cargo tanks, which has been properly crude-oil washed and water-rinsed, shows that about 90 per cent of the ballast water can be discharged with less than 15 ppm oil content. The oil content can be further reduced with improved oil removing equipment and operational procedure. Gravity separations can be very efficient for a ballast voyage of some duration. This is the cheapest, simplest and most used procedure. By comparison, oily water separators on the market will reduce the oil content in the treated water to around 25 ppm. To reduce mechanically the oil contents further is very costly.

Fresh water ballasting projects have initiated research on new techniques for separation of oil and water in order to render water transported in oil tankers suitable for multi-purposes. By the application of simple ceramic or filter granulate oil absorbent material developed in Japan, or by pumping water contaminated by crude oil through multi-oil absorbent filters, the level of oil contents can be reduced to less than 1 ppm. Fresh water contaminated by crude oil or other petroleum products can thus have its pollutants removed at very low costs. Other treatment processes to upgrade the contaminated water to potable standards involve sand and activated carbon filtration and chlorination.

Another suggested measure to treat oil-contaminated ballast water is the application of a special oil degradation bacteria. Provided certain conditions are met, this bacteria will degrade hydrocarbons in ballast water. Degraded oil would act as a fertilizer medium, making such treated water suitable for irrigation.

(e) Health considerations and quality monitoring of imported water

The Drinking Water Standards of the World Health Organization (WHO) are based on review of all aspects of drinking water quality with some guideline values for water which is safe and acceptable to the consumers. The limits set for organisms, or chemical substances that are potentially hazardous to consumers, do not consider vast quantities of water transported in oil tankers from one area of the world to another. It is imperative to ensure that imported water does not contain undesirable properties which may have adverse effects on soil, crops or human beings. In the evolution of fresh water ballasting, an issue of prime importance is whether fresh water that has been contained in an oil tanker for days or weeks at ambient temperature, suffers any deterioration in quality as to severely limit the possibilities for its subsequent uses. The possible effect of such changes depends to a marked degree on the intended use of the water and, in particular, whether it is intended for potable or non-potable purposes or, for the irrigation of edible or non-edible crops. It is well known that the greatest potential health hazard associated with the public water supply is the possibility that it could become a vehicle for the spread of a water-borne infectious disease, as experienced by some developing countries.

As long as the water is supplied from regions where the water is raw and untreated high quality mountain water, the risk for the spread of water-borne diseases can be considered rather remote. When the water supply source is from areas where infectious diseases are known, then great care must be exercised to prevent the spread of unwanted pollutants by tankers. The WHO guidelines for drinking water quality at the source should be the best guarantee that it is acceptable to consumers in recipient countries and the quality would certainly be suitable for most agricultural and industrial uses. The WHO guidelines, therefore, provide a good comparison for evaluating the quality of water of a suitable standard for shipment.

Differences in the characteristics of the water that is loaded at the various locations, and any contamination by sea water during passage, could lead to problems. Routine monitoring of the composition of fresh water taken on board and discharged from tankers is therefore essential. This principle is, however, well established in shipping. Commodities shipped on board vessels under transportation contracts duly recognize the need for quality and quantity controls to ensure that the commodities as shipped, are of the same standards when delivered to receivers at their final destinations. Problems which may arise by virtue of the possible existence of organisms in the water such as fungi, viruses etc., which may be harmful to plants, and/or inorganic material which could be harmful to humans, should be eliminated by proper water control and treatment prior to any uses at the places where the water is landed.

## 4. Water quality and uses

### (a) Potable water

Analysis of the most common components of exported water from European ports shows a very low level of chlorine. The cleanliness of raw mountain surface water make it most suitable as a source for the supply of drinking water.

To avoid any pollution, water for drinking and other domestic purposes can most safely be transported in tankers which will only be used for water transportation purposes. As long as water is considered a low-cost commodity, there are limitations on the trading distance where water can be delivered more economically than the cost of producing water by desalination. Backhauling of water as clean tanker ballast would not place such restrictions on the length of the voyages.

When water is carried in properly washed and cleaned cargo tanks, the situation will be largely associated with the conditions in segregated water ballast tanks. Cargo tanks can be coated in a way that will prevent corrosion and degradation of the water quality during transportation. Water quality control measures, to check cleanliness and compliance with the required standards for imported water after treatment, should be the same as for the local waterworks in the water recipient countries.

(b) Water for irrigation

Some arid Middle Eastern countries may have good exploitable underground water resources, but projections for agricultural water demand are being carefully studied, as overpumping of local supplies has also created severe shortages. Indiscriminate water use in the traditional irrigation sectors has also caused serious cutbacks in the production capacity of the soil, as fertility deteriorates when salt accumulates. For the time being, the demand for water can be met by depleting accumulated reserves, but overdraft of the natural resources cannot continue indefinitely. This is also increasing the emphasis on the reuse of sewage for irrigation. One source estimates that if the present pumping rate in Kuwait continues from underground wells, salinity will increase to 6,000 ppm in a few years. Similar examples can be seen in other arid countries where the supply of ground water is dependent on the extent of scarce rainfall.

The water imported for irrigation gives considerable freedom as to its source. Certain hygienic health standards do have to be met, however.

The water used should be free from hazardous chemicals and uncontaminated with organisms likely to be harmful to plants. Before harvesting, it is undesirable to use contaminated water on crops which are consumed raw. Some pollution can be tolerated, but the difficulty is to define permissible limits. The pH of the irrigation water ought to show a reading of between pH 5.0 and 7.5 as critical limits.

General characteristics to be applied for irrigation water:

(i) Low salt level, suitable for direct use in irrigation, including drip feeding and hydroponic culture routines;

(ii) Pollutant concentrations sufficiently low to ensure neither direct contamination nor bio-accumulation problems in produced crops;

(iii) Free from disease-producing organisms;

(iv) Free from health hazards presented by microbiological contamination;

(v) Maintenance of soil fertility and soil microbiology balance.

When applying oil-contaminated water for irrigation, a new factor of some uncertain dimension is introduced. The importance and magnitude of this factor can only be tested by experimentation. Some introductory research has been undertaken on the effect of oil-contaminated irrigation water on the growth of some vegetables. These trials have been performed in Norway under greenhouse conditions since 1978. Some chemical analyses of aromatic compounds were undertaken on sweet pepper and tomato. The results of these analyses showed that there were only traces of nephthalene, fenatrene and dibensotiophene compounds taken up by the plants. Similar tests performed by the Nodai Research Institute of the Tokyo University of Agriculture in Japan and by the National Academy for Scientific Research in Tripoli, Libya, have so far been encouraging. Water with an oil content of 50 ppm or less seems to cause no problem with regard to absorption of metals or hydrocarbons.

(c) Industrial water

There are many ways in which water is used in industry - the quantity and quality requirements depending upon the nature of the process. It is understood, however, that an oil content of up to 1 ppm would be acceptable. Oil-free water can, if required, be provided by tankers when carried in segregated ballast tanks.

(d) Contingency water

Improved water balance is also a matter of better awareness of national water contingency to cater for accidental, occasional, seasonal or emergency supply gaps. Diversification of water resources is desirable, with the aim of reducing risks for temporary interruption of vital water supplies. Desalination of sea water requires pollution-free water at the source. Polluted water or interruptions in supplies of energy necessary for water production may temporarily cause the closing down of desalination plants. Supplementary water from overseas sources could be made available on short notice once water export sites are established. Water authorities should see the benefits of providing a level of such supplies in national water supply policies.

The challenge of the "Water Decade", to which so many nations around the world are responding, is to make safe water available when at the same time thousands of men, women and children are suffering from the lack of water which can be due to a drought which has lasted longer than people are used to experiencing. Without emergency supplies of water such people may have to leave their homes in efforts to survive. To help in this situation a water shuttle emergency scheme can be implemented for supply of water to coastal regions where the tankers can pump their waters ashore.

## 5. Economic aspects and cost comparisons

### (a) General

Apart from environmental benefits which might be achieved by implementing fresh water ballasting and the carriage of water in cargo tanks on return journeys, tankered water supplies also provide for alternative sources of water to desalination. Due to the overcapacity in tanker availability, the oil transport market has declined alarmingly, so that any cost based on time or lost opportunities which may stem from carrying fresh water on ballast legs have been significantly lessened. Moreover, flared gas, which had been used as a free energy source for desalination is now used in petrochemical manufacture, making desalination more expensive when inputs are valued at real resource prices which are put into the process.

When considering the cost of the water, one has to take into account cost of water at source, which would include the cost of infrastructure for loading the water. Depending on the amount of water loaded for the return journey, some delay costs may occur in loading the water. If the loading port is not the same as the oil discharge port, then some costs for diversion might occur. At the unloading port the discharge of 30 per cent ballast can often take place while loading, but a ship with a much higher percentage often needs to deballast before commencing oil loading. The cost of purification before distribution should also be included in the cost of imported water. The cost of purification depends on the water use and the extent of cleanliness of cargo tanks at the port of loading.

### (b) Backhauling fresh water

Whereas the total economy of fresh water importation schemes depends on a number of factors, the transportation costs for backhauling are directly related to the crude oil tanker market. The ship operator evaluates water transportation from a cost/revenue angle. With the depressed tanker market today, revenues hardly cover the transportation costs. Almost any economic contribution that exceeds the incremental costs connected with a deviation involving alternative work is of interest. On a good tanker market, the revenue from water transport deviation will have to be compared with the alternative income from oil transportation.

Fresh-water backhauling involves a set of deviations varying with the location of the water port, quantity of ballasting and the extra time needed. The transportation cost per cubic metre of fresh water calculated on this basis is of a minimum cost - or breakeven cost relative to an oil voyage - when no profit incentives are included for the tanker operators.

The buyer of fresh water, who is the one to assume the extra costs for water ballasting, will need to compare delivered fresh-water costs with other available water supply alternatives and energy availability.

If fresh water supply and reception facilities are available in the oil discharging and loading ports, respectively, there will be no extra cost incurred for the time lost to transport a quantity of fresh water corresponding to the normal ballast requirement. Although the transportation costs are virtually nil, this alternative may not be the most attractive for large scale fresh water transportation schemes for several reasons. In addition to the problem of water availability, considerable investments would have to be made in a number of oil loading and discharging ports.

There are a number of backhaul transportation alternatives which will give different transportation cost figures. In the figures presented below, it is assumed that 100 per cent of the carrying capacity of the tankers is utilized for water cargoes and that the maximum tolerable oil concentration in the water at the receiving end is 15 ppm. Four fresh water trade routes were evaluated for 250,000 dwt and 350,000 dwt tankers.

Those routes were: Rotterdam - Middle East Gulf (Cape route); Cape Finesterre - Middle East Gulf (Cape route); Dominica (Caribbean) - Middle East Gulf; Yakushima - Middle East Gulf. The economic evaluation was based on a reasonable range of the tanker market conditions.

If the oil cargo from the Gulf area is destined for a Mediterranean or North European port, then the vessel is likely to return via the Suez Canal. Currently, the vessel can only be partly laden with fresh water when transitting the Suez. However, on other transportation routes, such as the Gulf to America (no Suez) and eastern destinations, the tanker may carry a full cargo of fresh water.

From the above assumptions, the following conclusions may be drawn:

(i) Within the assumed range of tanker market conditions, the backhaul transportation cost of fresh water ranges from about $US 1.00 to $2.00 per $m^3$ ($3.8 to $7.6 per 1,000 U.S. gal).

(ii) There is very little difference in transportation costs between a 250,000 dwt tanker and a vessel of 350,000 dwt.

(iii) The transportation costs are very sensitive to the time needed for deviations and delays on a water voyage in relation to a normal ballast voyage. Fresh-water supply ports should therefore be suitably located relative to the major oil routes to reduce deviations and at such a distance from the oil discharging port to allow tank cleaning to be performed en route to the fresh-water loading port without delays. Furthermore, a fresh-water loading and discharging port should be designed to reduce port operation time to a minimum.

(iv) The transportation cost of fresh water is closely related to the minimum oil contamination requirement at the receiving end. If treatment facilities for oil removal are to be installed in the water discharging ports, then no tank cleaning will be necessary in addition to crude oil washing. In such a case, a trade from the oil discharging ports, having large quantities of fresh-water supplies available for shipment (e.g. Rotterdam), will give the lowest fresh-water transportation costs.

Most quotations on the price of water at the source will depend on the amount of water which can be shipped annually from a water site. Prices may vary between $US 0.20 TO 0.75 per $m^3$ free on board (FOB). The cleaning process of water and oil removal can be in the range of $US 0.05 - 0.20 per $m^3$. These costs come in addition to the ocean transportation costs which are the revenues to be paid to tanker operators.

(c) Dedicated fresh water carriage

The use of oil tankers in a shuttle service between water loading and discharging ports will be a high cost operation compared with the low commodity value of the water.

The most significant parameters influencing the transportation costs of a shuttle service operation are the ship size and the distance of the round trip voyage. The larger the vessel and the shorter the round trip distance, the lower the transportation cost will be. This is shown in table 24.

Table 24. Shuttle service transportation costs
(US dollars per 1,000 gallons of water)

| Roundtrip distance (miles) | Ship size (DWT) | | | |
|---|---|---|---|---|
| | 100,000 | 150,000 | 230,000 | 300,000 |
| 2,000 | $10.56 | $8.55 | $6.32 | 5.79 |
| 4,000 | 15.56 | 12.26 | 9.27 | 8.25 |
| 6,000 | 20.52 | 15.90 | 12.23 | 10.71 |
| 8,000 | 25.55 | 19.61 | 15.18 | 13.17 |
| 12,000 | 35.43 | 26.91 | 21.01 | 18.05 |
| 16,000 | 45.46 | 34.29 | 26.91 | 22.98 |
| 20,000 | 55.38 | 41.60 | 32.74 | 27.86 |
| 24,000 | 65.33 | 48.94 | 38.61 | 32.74 |

Three main water sources have been considered for shuttle services to Mina al Ahmadi, Kuwait and Jubail, Saudi Arabia. These are: Shatt al Arab, Iraq; Indus River, Pakistan; and Reunion, Indian Ocean.

The transportation cost of fresh water in a normal oil tanker for about 100,000 dwt from Shatt al Arab (Khor al Amaya) to Mina al Ahmadi and Jubail, a round voyage distance of 180 to 380 miles, will be of the order of $1.60 to 1.70/m$^3$ or $6.10 to 6.40/1,000 US gal. The transportation distance is very short and the ship will spend most of the time loading and unloading. The actual transportation costs will therefore depend very much on the efficiency of the port operations.

Taking water from the Indus River over a distance of about 1,000 miles to Mina al Ahmadi and Jubail gives a transportation cost of about $2.80/m$^3$ ($10.60/1,000 US gal) for a 100,000 dwt tanker. If there are no draft restrictions, larger tankers may be used and the corresponding transportation cost for a 300,000 dwt tanker would be $1.50/m$^3$ ($5.70/1,000 US gal). It should be noted that the use of obsolete vessles rendered out of standard for the transportation of oil and acquired for the sole purpose of transporting water on designated routes, should reduce the transportation costs of water significantly.

The transportation distance from Reunion to the Arabian Gulf is about 3,300 miles. A shuttle service over this distance does not seem to be economically justified for a modern 100,000 dwt oil tanker. For a 300,000 dwt oil tanker the transportation cost will be of the order of $3.00/m$^3$ ($11.40/1,000 US gal).

As will appear from the above, the transportation economy is very sensitive to the ship size, the transportation distance and whether the tanker is taken out of the oil trade. The use of large vessels on very short shuttle routes gives the lowest transportaton costs.

(d) Arrangements for fresh water carriage

It is imperative for fresh-water transportation projects that water exporters receive concessions to export water from the source, with reference to quantities of water available for shipment year round. The concession should confirm water availability for an indefinite period of time (10 - 20 years), which might be a requirement for importers of water who may become dependent on water importation.

Harvesting of water in the Antarctic from drifting icebergs offers simpler entitlement to the source. Water from unpopulated islands would likewise not compete with local demands as may be experienced in populated areas.

One assumption for fresh water trade is that there is a water seller and a water purchaser. At the water export location it appears that those who should initiate fresh water ballast as a marketable resource (i.e., oil companies, tanker operators) may not show particular interest, except where the fresh-water ballast benefits their own operations. In some instances, petroleum-receiving facilities are adjacent to municipal or private water districts with adequate excess water capacity to engage in fresh-water export. There has already been some interest in several water districts to supply petroleum tankers with fresh-water ballast at their industrial/commercial water rate. The basic question today is whether there are interested purchasers.

Under the present freight market conditions with redundant tonnage available, suitable vessels will become available for what might be transportation needs. Contractual arrangements can be negotiated once there is a market need.

## 6. Non-conventional fresh water supply schemes

### (a) Water demands

In arid countries also utilizing desalted water, four different qualities of water exist. The first is potable water from fresh-water well fields with a total dissolved solids (TDS) content up to approximately 1,500 ppm. The second quality of water is brackish. This water has a TDS of up to 5,000 ppm and usually comes from wells in or around coastal towns. Brackish water is now used mainly for irrigation and blended with distilled water to make domestic water supplies more palatable. The third type of water is product water from desalination plants where TDS ranges between 30-500 ppm. The fourth type is reclaimed sewage from towns and industrial waste-water.

There are about 500 Multi-stage Flash (MSF) desalination plants in operation worldwide with a total installed water production capacity of some 2.3 million $m^3$ per day. Some 75 per cent of these plants are located on the coastal areas around the Arabian peninsula. Some of these units may produce fresh water at a cost of around $US 3-6/$m^3$ or more. Such plants also contribute significantly to electric power generation in some locations. To what extent such plants can meet future growing water demands is questionable. As large scale sea-water desalination involves the return of waste brine, the salinity of the nearby sea can be overenriched, endangering fisheries, marine life and disturbing the ecological balance.

In seven countries (Saudi Arabia, Libya, Kuwait, United Arab Emirates, Bahrain, Qatar and Oman) the total water consumption for municipal purposes is estimated to be around 1,200 million $m^3$ per annum. The amount of water used for agricultural irrigation is estimated to be ten times as much. By the year 2000 it is believed that the total water needs in these countries will have tripled in comparison with present uses. Similar trends will be seen in oil-importing developing countries, with increased productivity and higher standards of living.

### (b) Towing of icebergs

In the early 1970s studies were initiated and suggestions were made that Antarctic icebergs might be towed to South Africa, south-west Australia, or even to California to alleviate shortages of irrigation water. Since then various private interests with Governmental involvement continued research and commenced to track movements on icebergs along the coast of eastern Antarctica.

The most remarkable development on iceberg-centred research, however, occurred following the disclosure of the seriousness of Saudi Arabian interests in icebergs by Prince Mohammed al Faisal al Saud in 1977. Since then there have been two international conferences on iceberg utilization under his sponsorship.

Optimistic assessments of the possibility of bringing icebergs to southern coastal destinations in Australia originally viewed the Amery Ice-Shelf as being the appropriate source for towing. The dramatic increase in fuel costs since the increases in oil prices during the last decade makes the economics of iceberg towage far less feasible. The possibility of iceberg towage seems to hinge on the ability to utilize the several principal currents which would transport icebergs from west to east and south to north.

Prince Mohammed al Faisal has for some time been sponsoring research, which the Norwegian Polar Research Institute in Oslo is conducting, on iceberg towing in the Antarctic. The size of the icebergs are gigantic and may contain as much as 15 million $m^3$ of water or more. Some 10 large tug boats would be required in a three-month tow dragging the iceberg northwards. Then the current is expected to move the iceberg eastwards to reach South Africa or Australia. The towage of large icebergs has not been tested in practice, but studies continue. Research is also being conducted on methods to cap the iceberg with some sort of insulation, so that it can survive a long distance tow in warmer waters. The ultimate goal for Prince Mohammed al Faisal is to move icebergs from the Antarctic across the Equator to the Saudi Arabian Peninsula.

The quantity of icebergs in the Antarctic is vast, but very few have reached a position and possess an inherent strength and sufficient size to be suitable for a long distance tow. Therefore some 20,000 icebergs classified by size and other qualities are being registered by visual observations and the use of automatic data transmitting buoys. Some icebergs have been observed in a distance less than 1,000 kms from both South Africa and Australia.

(c) Water resources problem areas

(i) Most oil-exporting countries situated in arid and semi-arid regions have ambitious plans to expand in various fields, including greater self-sufficiency in food production. Access to more supplementary water for irrigation would stimulate plant production as well as improve the landscape and, in general, the human environment. Ecology considerations favour supplementary tanker water supplies, which also can be recharged into underground wells in coastal areas to prevent saline intrusion.

Treated waste water from industry, urban areas and refineries contains chemicals and salt which are detrimental to plant growth. Refinery waste water also contains phenols which have to be diluted for irrigaton purposes. A dilutent medium to improve the quality could be water from incoming tankers. It is encouraging to note that experiments are being done by the Kuwait Institute for Scientific Research on the use of refinery waste water for irrigation.

(ii) Mexico's major concern is the Colorado River which, for most of its length, flows through the United States before cutting through Mexico to the sea. Extensive irrigation and damming of the river by the United States has reduced the flow of water to Mexico and has increased the river's salinity to a point where agriculture in the fertile Mexican Valley has been seriously affected. This will necessitate the construction of desalination plants. After years of negotiations between the two Governments, a treaty was concluded in which the United States acknowledged its obligation to take action to prevent continued contamination of the Colorado River and to compensate Mexico for damages. As a result, the world's largest desalination plant is to be built near the border to return treated water to the river for use in Mexico. An additional supply of water from supertankers could assist in solving the problems.

(iii) A chronic shortage of water is also anticipated in the state of California, where the present consumption exceeds the renewable supplies by more than 12 per cent. In southern California the recharge of ground water with sewage effluent has been practised for over 10 years. Imported or natural spring water is blended with about 12 per cent sewage-treated effluent and the mixture is recharged by surface spreading. Sewage effluent is also being injected directly into potable water aquifers in southern California to form a barrier to sea-water intrusion. Tanker water supplies could assist in improving this situation.

(iv) Some islands in the Caribbean Sea are suffering from water shortages. With no cheap energy available, the building of desalination plants and long distance water piping to meet the demands would be very costly. Already water shuttle services are available in some locations and have appeared highly competitive with the building of desalination plants. A water management regime in that region could more readily adopt tanker water supplies.

(v) The Riyadh water transmissioin system, currently under construction, is designed to transport potable water produced by the desalination plants of Al-Jubail on the east coast of the Kingdom of Saudi Arabia to a terminal near Riyadh. The initial design capacity of the system shall be 623,000 $m^3$/day, with the final design capacity of 830,000 $m^3$/day. Reliability of the whole system, including the provision of adequate reserve storage for water to maintain an essential supply in the event of any temporary destruction or malfunction of the system, is of great importance. Tanker water supplies can be supplementary to this system. Tankers can also receive brine from the large desalinaton plants and discharge it outside protected areas where no harm is done to the marine environment.

(vi) Libya is in the process of studying a fresh water ballast scheme. This will, if found to be feasible, provide financial incentives for oil loading terminals to install deballasting facilities required under MARPOL 73/78.

(vii) Some East African countries can improve the water supply situation in local regions where there is arable land, but well water is too saline for irrigation. Such water can be rendered suitable for irrigation if mixed with imported fresh water.

(viii) In the Canary Islands water consumption already greatly exceeds all renewable supplies. The deficit is being made up by mining ground water. The economy of the island is based on irrigated cultivation of tomatoes and bananas and on a growing tourist industry. In recent years, however, the most important market commodity has been water, the bulk of which is privately owned. At the present rate of extraction, all the available water will have been exhausted within two decades. If agriculture is to survive in the Canary Islands, drastic changes in water policy will be needed.

(ix) A water shuttle service is under study for shipment of water from the South of France to the Cape Verde Islands. Water production costs by desalination would exceed those of importing water by shuttle tankers.

(x) Energy generation will also create serious environmental problems in the future, as will the production of water by desalination. Experts estimate that in Arabian oil-exportings nations, application of improved oil-recovery techniques will require injection of water to oil wells to maintain oil pressure. In order to preserve ground water, sea water is now being used. This procedure may have serious repercussions if the injected sea water should interfere with underground water-bearing formations. In some locations the injected water could be brought in by tankers in return for oil. Such injected water could be a source at a later date.

## 7. Conclusions

Water, not oil, is considered by many as our most valuable resource, and its availability is reaching critical levels in many regions of the world. Water transportation by tankers not only represents non-conventional trading opportunities for tankers, but it also offers a service to societies at large. With the implementation of new environmental regulations for tankers, about one third of the world's tanker fleet will be rendered out of class for a carriage of oil in coming years.

Fresh-water ballast and water shuttle services are concepts whose applicability is limited to selected sites where the water may be regarded as a trade item. Compared with total water demand in most countries concerned, the possible supply by tankers is significant, but not enormous. It should never be other than an additional source forming a relatively small, but important part of total national water supply and water contingency.

Fresh water trade via oil tankers is possible when it meets the economic requirements of participating parties. In cases of emergencies, however, the cost factor for supplying water may not be the deciding factor. The supply of water by tankers is a major challenge which deserves careful consideration by authorities in areas where a scarcity of water persists.

Dependence on foreign water resources by involvement of tanker transportation should not hinder the security of water-receiving nations. Close co-operation between interested parties and actions by Government are essential for further progress.

There is a strong economic and social incentive to consider water transportation by tanker as an alternative to desalination. The environmental benefits and protection of the marine environment should be observed. Most significant is the savings in energy that would result, considering that the use of desalinated water is expected to grow at a rapid rate for the next few years.

The status of negotiations on water projects cannot be given in detail, but there has been growing acceptance of water transportation, and much encouragement to support any efforts to export water by tankers. There are many variations on possible projects which have been outlined. Dedicated vessels carrying nothing but pure drinking water may one day become an economic reality on a larger scale. The ballast water concept can certainly be applied along the oil tanker routes.

What is certain is that the demand for adequate supplies of fresh water will be growing. The worldwide challenge to supply the water needed will last at least for the remainder of this century. Water sales from water-rich countries to water-poor countries serve the interests of both. Tankers are available and, therefore, the key link between the two already exists and is in operation, the worldwide tanker fleet.

## B. Maritime transportation of fresh water

by J.W. Hargreaves*

### Introduction

Transportation of water by vessel is not a new or untried concept. Vessels have carried water in relatively small volumes through the ages. The concept under discussion is different, however, in that it is now believed that circumstances have arisen whereby large volumes of water can be carried over long distances in vessels which normally carry other liquid products such as heavy oils, refined products and liquid chemicals.

The concept takes advantage of the fact that much of the world's tanker fleet is sailing part or all of one leg of a round trip in ballast. It is also significant that much of this shipping is travelling between countries with surplus supplies of water and those which are dependent in the main on treatment of saline or brackish water or which do not have the finance to take advantage of their existing resources or develop alternative sources.

In principle water is considered as the backhaul cargo, in which ship operators take advantage of utilizing vessel capacity to carry a low-cost commodity on the return journey, thus offsetting the high costs of moving vessels long distances in ballast.

Bearing in mind that in the region of 350 million tons per annum of liquid cargoes are moved from the Arabian Gulf and North Africa to importing countries in North America, Europe and South-east Asia, the question has to be asked as to why transportation of water is not taking place on a large scale today. The answer is not simple, but until recently the disadvantages outweighed the advantages. However, many now believe that there has been a sufficient shift in the balance to enable the business to take off. Factors such as the significant decrease in demand for oil, the large over-capacity of the world's tanker fleet, the introduction of new types of vessels, the existence of ballast reception facilities and treatment plants and the value of some forms of energy which were once considered to be free, now make water transportation more economically attractive.

It would be unrealistic to claim that water transportation is the answer to the world's water shortages. In some situations, importation can provide a simplified and cost effective alternative, but in general the concept should be seen as a supplementary rather than alternative source of supply. Although water is considered by man to be a fairly simple commodity to manage, those with experience in providing communities with a constant, uncontaminated supply will appreciate that the water industry has its own specialized problems which should not be underestimated. In this respect, maritime transportation of water has its own problems, which have to be resolved in addition so as to preserve the integrity of the cargo.

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## 1. IMO's interest in water transportation

Before considering the various aspects of water transportation, it is worth indicating why IMO is interested in the concept. One of the main objectives of the International Maritime Organization (IMO) is to promote the adoption by Member States of measures designed to prevent and control maritime pollution by ships. The latest international regulations are contained in the International Convention for the prevention of pollution by ships 1973, as modified by the Protocol of 1978, which is generally referred to as MARPOL 73/78. This protocol entered into force in October 1983.

The principle concern for marine pollution lies with the discharge of ballast to sea. The ballast water of vessels carrying crude oil can lead to the discharge of several hundred tons of oil, if no precautions are taken. IMO conventions implicitly require tankers to operate in such a way that the major proportion of this oil is retained on board using a technique known as load-on-top (LOT). On shorter voyages, however, there is insufficient time to carry out LOT, and in areas where the discharge of any oil is prohibited oil-loading terminals are required to provide dirty ballast reception facilities.

There are a number of cases where deballasting facilities have not been provided, mainly for economic reasons. IMO's interest is promoting water transportation in general and more specifically as fresh water ballast stems from a desire to create the situation where revenue derived from the operation of reception facilities suitable for fresh water ballast would make the provision of such facilities economically viable. In such cases the fresh water would be taken on shore, and after oil removal, used for irrigation or industrial purposes. The oil recovered would also contribute to the cost justification of the operation.

The objectives of this paper are to consider the various methods for water transportation, the facilities that are required to deliver water of different quality standards and the problems which require consideration.

In preparation of the paper the author has drawn on experience gained in exporting drinking water from the United Kingdom to Gibraltar.

## 2. The resource: Quantity and quality

For water transportation to provide a reliable method of supply, the importing country has to ensure that there are abundant and secure sources of good quality water, ideally on or close to the world's main tanker routes. Some 15 or so such supplies are availableworld wide (Meyer, 1983). However, it is worth outlining the criteria that should be considered when selecting a source of supply.

### (a) Quantity

The following are considered as important in terms of quantity of supply.

(i) The exporting country should be able to guarantee the quantities required by the client for 365 days per year and irrespective of rainfall or lack of it.

(ii) The supply should be from countries which have a stable political, social and economic structure.

(iii) The exporting region should have an infrastructure which is sufficiently robust and flexible to support the supply on a continuous basis.

(b) Quality

In general terms the quality of water to be exported should be predictable and should be compatible with the intended use.

The dangers of introducing chemical and microbiological contamination are obvious; therefore, selecting a source which minimizes these risks of importing water containing high levels of contaminants is important. To a certain degree the risk can be reduced by treatment in the recipient country but if possible treatment should be avoided where it is not required because of cost implications. The quality requirements are considered below.

(i) Drinking Water

Water which is transported as drinking water (i.e., has been treated in the exporting country) should be maintained in a condition which meets the international standards applicable in the recipient country. In general, water which meets World Health Organization (WHO) standards would be acceptable to most countries.

Ideally the quality of the "raw" water before treatment should be such that if treatment fails for any reason, the water would not contain contaminants which would present a health risk in the recipient country. In this respect, since potable water would receive additional disinfection before being put into the domestic supply in the recipient country, the risk from normal bacteriological content is not considered a problem.

(ii) Raw water intended for human consumption after treatment

In this category the quality of the water would have to be high, with relatively low levels of chemical contaminants and the absence of microbiological agents which are known to resist treatment or are difficult to remove. Suitable standards are suggested in table 25 for water which would be treated in the recipient country before use. To some extent, the choice of raw water would depend on the type of treatment available in that country.

(iii) Agricultural use

The number of sources of raw water which are suitable for agricultureal use are considerably larger than for potable water. However, because the water is unlikely to receive treatment (other than oil removal), then it is important to consider the quality of the product at source.

The danger of introducing plant pathogens or parasites needs careful consideration. Similarly, levels of toxic and accumulating metals and organic chemicals such as pesticides are important.

Table 25. European quality standards for surface waters for use as drinking water

| Parameters | $A_1$ | $A_2$ | $A_3$ | Units |
|---|---|---|---|---|
| pH | 6.5-8.5 | 5.5-9.0 | 5.5-9.0 | |
| Colour | 20 | 100 | 200 | mg/11 Pt scale |
| Total Suspended Solids | 25 | | | mg/1 SS |
| Temperature | 25 | 25 | 25 | $^oC$ |
| Conductivity | 1,000 | 1,000 | 1,000 | $us/cm^{-1}$ |
| Nitrates | 50 | 50 | 50 | mg/1 $No_3$ |
| Fluorides | 0.7-1.0 | 0.7-1.7 | 0.7-1.7 | mg/1 F |
| Dissolved iron | 0.3 | 2 | 2 | mg/1 Fe |
| Manganese | 0.05 | 0.1 | 1.0 | mg/1 Mn |
| Copper | 0.05 | 0.05 | 1.0 | mg/1 Cu |
| Zinc | 3 | 5 | 5 | mg/1 Zn |
| Boron | 1.0 | 1.0 | 1.0 | mg/1 B |
| Arsenic | 0.05 | 0.05 | 0.1 | mg/1 As |
| Cadmium | 0.005 | 0.005 | 0.005 | mg/1 Cd |
| Total Chromium | 0.05 | 0.05 | 0.05 | mg/1 Cr |
| Lead | 0.05 | 0.05 | 0.05 | mg/1 Pb |
| Selenium | 0.01 | 0.01 | 0.01 | mg/a Se |
| Mercury | 0.001 | 0.001 | 0.001 | mg/1 Hg |
| Barium | 0.1 | 1.0 | 1.0 | mg/1 Ba |
| Cyanide | 0.05 | 0.05 | 0.05 | mg/1 Cn |
| Sulphate | 250 | 250 | 250 | mg/1 $SO_4$ |
| Chloride | 200 | 200 | 200 | mg/1 Cl |
| Surfactants | 0.2 | 0.2 | 0.5 | mg/1 lauryl sulphate |
| Phosphates | 0.4 | 0.7 | 0.7 | mg/1 $P_2O_5$ |
| Phenols | 0.001 | 0.01 | 0.1 | mg/1 $C_6H_5OH$ |
| Dissolved hydrocarbons | 0.05 | 0.05 | 1.0 | mg/1 |
| Polycyclic aromatic hydrocarbons | 0.0002 | 0.0002 | 0.001 | mg/1 |
| Pesticides (drins) | 0.001 | 0.0025 | 0.005 | mg/1 |
| Chemical oxygen demand (COD) | | | | mg/$0_2$ |
| Dissolved oxygen | >70 | >50 | >30 | % $0_2$ |
| $BOD_5$ | <3 | <5 | <7 | mg/1 $0_2$ |
| Nitrogen | 1 | 2 | 3 | mg/1 N |
| Ammonia | 0.05 | 1.5 | 4 | mg/1 $NH_4$ |
| Total Coliforms $37^o$ | 50 | 5,000 | 50,000 | /100ml |
| Faecal Coliforms | 20 | 2,000 | 20,000 | /100ml |
| Faecal streptococci | 20 | 1,000 | 10,000 | /100ml |
| Salmonella | 0 in 5,000 ml | 0 in 1,000 ml | | |

Notes:

$A_1$ = Simple physical treatment and disinfection.
$A_2$ = Normal physical treatment, chemical treatment and disinfection.
$A_3$ = Intensive physical and chemical treatment, extended treatment and disinfection.

To some extent the quality of the raw water required depends on the type of crops as well as the soil on which it will be used. Importers also need to be aware of the concentration factor caused by evaporation. In this respect the concentration of the total dissolved solids content of the water at source is important. A maximum of 300 mg/l has been suggested by Marson (1983). This level allows for evaporation and the subsequent increase in chloride and sulphate ions. Table 26 provides some indication of the quality that is required. Needless to say, the better the water quality at source, the lower the risk factors involved.

(iv) Industrial use

There are many ways in which water is used in industry; the quality requirements therefore depend upon the nature of the process. Quality requirements range from drinking water quality for use in industries such as bottling, canning and the pharmaceutical process to poor quality water for use in heavy industry for cooling or some process water or in the oil industry for use in oil recovery techniques.

Even in these situations, importers need to consider the potential hazards of introducing unwanted contaminants.

## 3. Methods of marine transport

There are several options available for transporting water in vessels, some of which have been used successfully, others as yet remain unproven on a commercial scale. The quantities of water that can be moved depend on the tonnage of shipping available for that option.

The options which are available are listed below.

(a) Vessels dedicated to water transportation. Water is carried in the cargo tanks on a shuttle basis. No other products are carried. Although segregated ballast tanks are favoured, they are not essential. Vessels without segregated ballast tanks would carry ballast in identified tanks retained for that purpose.

(b) Product and chemical carriers which can be cleaned to accept water as backhaul cargo. The water is carried in lined product tanks which are isolated from ballast. Again segregated ballast tanks are favoured.

(c) Black oil carriers which have the facility for crude oil washing. Those which have segregated ballast tanks are preferable. The water is carried in the cargo tanks up to 100 per cent of carrying capacity.

(d) Black oil carriers or other vessels which are large enough to enable them to carry a significant volume of water in segregated ballast tanks. The water is carried as fresh water ballast either on the backhaul or as part of the load.

(e) Barges or dracones dedicated to water transportation. These are mainly restricted to smaller volumes, over shorter distances in inshore waters.

Table 26. Proposed standards for fresh water imported into an arid country for irrigation, after treatment

| Material | Maximum Amount (mg/litre) | Remarks |
| --- | --- | --- |
| Total oil | 10 | As determined by spectrophotometry |
| Suspended solids | 25 | |
| Net COD | 10 | = Total COD - Oil x 3.4 |
| $SO_4''$ | 100 | Total $SO_4''$ + Cl' less than 175. |
| Cl' | 100 | |
| $NO_3'$ | 100 | |
| Hardness (as $CaCO_3$) | 200 | |
| Total Dissolved Solids | 300 | This total over-rides the sum of separate electrolytes. |
| Sulphide, S" | 0.1 | |
| CN' | 0.05 | |
| Iron | 0.3 | As either Fe" or Fe"' |
| Manganese | 0.05 | |
| Boron | 0.5 | Less if boron-sensitive crops grown |
| Fl' | 1.0 | |
| Heavy Metals | | |
| Arsenic | 0.01 | |
| Cadmium | 0.005 | |
| Total Beryllium + Cobalt + Nickel | 0.05 | |
| Copper | 0.05 | |
| Mercury | 0.001 | |
| Lead | 0.05 | |
| Selenium | 0.01 | |
| Zinc | 0.5 | |
| Synthetic detergents (anionic) | 0.5 | |
| Phenols and phenolic compounds | 0.1 | |
| Organic chlorine | 0.1 | N.B. If necessary check specifically for DDT or Dieldrin |

Source: H.W. Marson, "The Separation of oil pollutants from water, with notes on other pollutants and on control procedures in the context of use for irrigation," Proceedings of the International Seminar on Fresh Water Tanker Ballasting, held at International Maritime Organization, London, 1983.

Note: The water should contain some dissolved oxygen and this will be present in any likely source. If absent, about 30 per cent of saturation will be obtained by dropping the water over a low weir.

4. Compatibility of methods of transport with quality requirements

The various options for transportation have limitations which are dependent on the quality of water required by the importing country. The following section considers the compatibility.

(a) Drinking water and industrial water demanding potable water standards

The shipping requirements for drinking water are by necessity the most demanding and stringent. In order to guarantee that the quality of the water is such that it can be used for human consumption strict codes of practice are required during loading, transportation and discharge. This applies whether the water is loaded as drinking water or as raw water which is then treated in the recipient country. In the latter case microbiological contamination does not present a significant problem, since treatment will render the product safe.

In order to achieve the standards required, vessels which are dedicated to water transportation (option 3a above) or product and chemical carriers (option 3b above) with segregated ballast which can be cleaned to an acceptable standard can be used. Depending on the configuration of the vessel and the condition of pumps, lines and ballast tanks, black oil carriers (option 3d above) can be used with water being transported in segregated ballast tanks. This system would necessitate the treatment of the water after discharge to an acceptable standard. Potable water (i.e. treated in exporting country) could not be safely transported in segregated ballast tanks. For smaller volumes barges or dracones can be used.

In all cases outlined above the vessel should be crewed by persons who are capable of ensuring the integrity and security of the cargo during loading, transit and discharge. Where vessels are not dedicated to water (option 3b above), knowledge of previous cargoes is important, since certain products may survive the cleaning process and will not be compatible with water intended for human consumption. In certain instances the previous cargoes can prove to be difficult to remove, thus increasing the cleaning time to an uneconomic level. These judgements can be made before a ship is fixed for water transportation.

Drinking water has been carried in dedicated vessels between the Suez and a port on the Egyptian coast. Similarly Caribbean islands have been supplied by this method. Drinking water is currently being transported from north-east England to the island of Gibraltar in product carriers. In this case water is considered as the backhaul cargo being loaded onto vessels which have discharged non-leaded refined products in European ports. The water does not require treatment after discharge.

(b) Agricultural and industrial use

Vessels which meet the requirements of drinking water are acceptable for agricultural and industrial water (options 3a and 3b above). The standard of cleaning and security during loading, transportation and discharge need not be as high. Nevertheless, where water is taken as backhaul, consideration of previous cargoes is still required so that unacceptable contamination does not arise. Water carried by this method does not require treatment after discharge and can be used directly for irrigation. In this situation the importer should select the source of water with discretion so as to avoid importation of high levels of contaminants.

If required, steps can be taken at minimum cost to ensure the water is safe for use.

If water transportation were reliant on using the methods of transport so far discussed, then the total volume of water which could be moved would be significant but not likely to meet the potential demand, particularly for irrigation water. In order to take advantage of the spare capacity in the world's tanker fleet, consideration needs to be given to utilizing vessels carrying black oils (option 3c above).

The use of black oil carriers on a routine basis would dramatically increase the volume of water which could be moved on a backhaul basis. Water could either be carried in cargo tanks (i.e. up to 100 per cent capacity) or as fresh water ballast (i.e. up to 30 per cent capacity). Mention has already been made of the use of vessels with segregated ballast tanks, but it is estimated that it will be 20 years before all vessels incorporate segregated ballast tanks. Therefore, at present many oil tankers carry ballast in proportion to their cargo tanks. Despite the introduction of crude oil washing and load-on-top techniques, cargo tanks still contain oil, up to an estimated 0.1 to 0.5 per cent of volume. Although these levels could be further reduced by improved procedures and design, water placed in the tanks will be contaminated by hydrocarbons and associated elements. Since water is a low price commodity compared with oil, in the United Kingdom or Western Europe owners are unlikely to invest in more sophisticated equipment and procedurea unless regular business in water can be guaranteed and facilities are available for discharge which do not interfere with their trade in oil.

Despite the apparent disadvantages of oil contaminated water, research indicates that after oil removal to an acceptable level, the water is suitable for irrigaton. In fact there are some indications that traces of oil are beneficial to plant growth, enhancing bacterial activity in the soil which in turn improves the soil condition and provides nutrients for plant growth. Various researchers have indicated acceptable levels of oil contamination. These range from 5 to 20 ppm and in some instances up to 50 ppm. To some extent the level at which phototoxicity occurs is dependent on the species of plant and for this reason it would be sensible to select a level of oil removal which will not damage the majority of crops but is cost effective to achieve. From the research carried out to date it appears that levels in range 5 - 10 ppm are likely to be acceptable to most crops tested.

Current methods of oil removal are capable of achieving these levels at economic rates. Gravity separators are utilized in deballasting facilities and can achieve levels below 20 ppm and less by use of more specialized methods such as the Pielkenrood or Kennicoctt separators. Below these levels, use of sand filters and activated carbon would be required.

While importation of uncontaminated water is preferable the lower cost of using large crude oil carriers (100,000 to 250,000 dwt) plus the cost of treatment remains attractive, where large volumes are required.

Where water is required for industrial use such as enhanced oil recovery methods from wells, water could be used directly from the vessel without treatment. This would only be cost effective where the imported water is replacing water of better quality which could then be used for higher grade purposes.

Despite the potential attraction of using black oil tankers for backhauling fresh water as cargo or ballast, there are few examples of where this has been carried out on a routine basis. Water for industrial use has been transported from Rotterdam to Curaçao and more recently from the Hudson River to the Caribbean island of Aruba.

Tons of water were taken from Scandinavia to Kuwait and Dubai as part of a research project.

Several oil producing countries have declared an interest in the concept and are actively investigating its feasibility. Many believe that water transportation will come into its own within the next decade.

## 5. Loading and discharge facilities

In addition to the method of transport there are two other aspects which require consideration, those of the loading and discharge facilities. With the introduction of deballasting facilities at many ports in the world and in particular in arid countries, the ability to discharge fresh water is more easily achieved than is the loading of vessels at present. Inevitably, some modifications will be required, but the basic requirements exist. It is therefore worth considering the fundamental requirements of loading and discharge facilities.

### (a) Loading facilities

The following summarizes the basic requirements which are necessary to service an efficient export facility. It is assumed that the exporting facilities will be on or near the main tanker routes.

The basic philosophy underlying the loading process is to maintain the integrity of the product while minimizing shipping costs. This is achieved by having:

(i) Port and berth facilities which are compatible with the maximum size vessel which might be used.

(ii) A robust and secure supply system from the water source to the loading arm which connects to the ship's manifold.

(iii) The ability to load vessels quickly while maintaining the quality of the product.

(iv) Good berth management involving personnel who understand the product and can deal with ship and port staff efficiently.

(v) An efficient and experienced scientific and engineering support service, capable of responding to any situation that might arise. A basic understanding of tanker design and cleaning procedures is also important.

(b) Discharge facilities

The facilities required for discharging water from the vessel will vary depending on the use of the water. However, the basic requirements can be summarized as follows:

(i) Off-shore facilities

Discharge from the vessel to shore can be achieved by use of a direct line into the on-shore facilities from the berth. Where port facilities are not compatible with the size of vessel in use, options such as single buoy moorings utilizing large tankers as off-shore reservoirs, barges and operation of a shuttle service in smaller vessels can be implemented. The overriding factor which must be considered is the cost of delaying the vessel while discharge takes place.

(ii) On-shore facilities

Where drinking water is being transported, the product can be pumped directly into the supply system, assuming that there is sufficient storage capacity in the system to absorb the volumes being delivered. Alternatively, drinking water can be pumped into on-shore storage tanks and then fed into the supply system. Where water requires treatment, either to attain drinking water standards or to reduce oil contamination before use, the water will require storage before and possibly after treatment. It is possible to utilize redundant oil storage capacity, although for treated water the tanks would require thorough cleaning prior to use. Experience has demonstrated that it is difficult to generalize on the facilities and operational system that will be required since no two locations are alike.

(c) Support services

Whether water is required for drinking, agricultural or industrial use, there remains a need for an effective scientific and engineering support service to ensure that quality of the cargo and the discharging procedures are satisfactory.

## 6. Advantages and disadvantages of water transportation

As with any system there are advantages and disadvantages of using water transportation as an additional source of water supply.

(a) Disadvantages

(i) The quantities available are dependent on shipping. While there may be overcapacity at present, this situation could change.

(ii) Countries which are not on the main tanker routes would be at a disadvantage.

(iii) Countries could become dependent on foreign sources.

(iv) Unless the source of water is selected carefully and the procedures (according to intended use) are adhered to, there is a possibility of introducing water-borne disease.

(v) As yet unknown problems associated with the use of oil-contaminated water may arise.

(vi) Deep water berths or single buoy moorings are necessary in order to optimize the costs of using the largest vessels.

(b) Advantages

(i) Large capital outlay is not required.

(ii) Compared with other alternatives such as desalination, transportation provides the importer with a low running cost, low technical requirement option.

(iii) The importer controls the quality and quantity required.

(iv) Transport of water fulfills an immediate requirement for water either in an emergency or where industrial development is faster than water can be supplied.

(v) The pressure on other resources during periods of economic growth or stockpiling can be reduced, thus increasing the overall security of supply in the longer term.

(vi) Shipping is utilized to a greater extent, which is particularly advantageous for countries which own vessels and are oil producers.

(vii) Energy is conserved and pollution reduced.

(viii) The quality of water can be significantly improved by blending with desalinated or brackish well water.

## 7. Market

Although emphasis has been placed on the movement of large volumes of water, this need not necessarily be the case. It is convenient to consider the potential market in four categories:

(a) Small islands and countries where importation of energy supplies to provide water by other methods is expensive and where the population demand exceeds the natural water sources.

(b) Countries which are self-sufficient in energy supplies, but where demand for that energy source elsewhere in the world is high and where the natural water resources are exceeded by demand from industrial/agricultural developments and population increases.

(c) Countries which have sufficient water but where the lack of finance prohibits the development of that resource.

(d) Countries which have neither the natural resources or the finance to import energy to provide water by other means.

The quantity and quality of water required under the four categories may be entirely different.

They could range from nany millions of $m^3$ per year to support agriculture, to a few hundred thousand to supplement existing potable supplies at certain times of the year. It is believed that transportaton by vessels can meet both demands and that the economic and technical feasibility of doing so is imminent.

## Summary

Water transportation is not a new concept; however, there remains a large potential which has yet to be utilized. One of the reasons for not taking up this option as a method of providing water is a general lack of understanding of the feasibility of the method. The argument that countries do not wish to be dependent on a foreign source is accepted, but in many ways water is similar to oil in terms of economic dependency. Since we are not talking about communities being totally dependent on foreign sources, the level of dependency can be minimized by good strategic planning. In this context importation should be seen as an additional source which can be integrated into any overall resource planning strategy. Where a country's natural water resources are dwindling through overuse, and there are financial constraints which prevent massive expenditure on other methods of providing water, importation has many advantages. Apart from the financial advantage of not requiring large investment, importation is a relatively simple, low technology, low labour intensive option where the client controls the quality and quantity requirements and where the onus is on the exporter to meet those requirements.

## Acknowledgements

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## C. Transport of drinking water in segregated ballast tanks

by C. Wielenga*

### Introduction

Water is present in nature in sufficient quantities to be able to meet total world demand. The availability of water is also guaranteed in the future. As a result of the natural cycle, not a drop of water is lost, and the available resources can never therefore be depleted.

Unfortunately, however, the supply of water is not distributed evenly. Whereas some countries have vast resources at their disposal, numerous others are faced with serious shortages.

In searching for solutions, our thoughts turn first of all to the supply of water by tanker, not only in order to supplement or replace existing desalination plants, but also to alleviate distress in countries where there is an urgent need for water, or where such a need is thought to be imminent. In this way Rotterdam can contribute to reaching the goals of the International Drinking Water Supply and Sanitation Decade.

### 1. The port of Rotterdam

The port of Rotterdam is the largest and busiest in the world. Its leading position is attributable among other things to its excellent facilities and infrastructure and its international role as an oil supply port. Since there is a constant movement of oil tankers, one important condition is met. Over 100 million tons of crude oil and crude oil products were shipped through Rotterdam in 1984. No other port in the world can boast shipments of a comparable size.

Moreover, large quantities of water are available in Rotterdam, drinking water as well as lower-quality fresh water, and there are also facilities for pumping the water aboard the tankers.

For the purpose of transporting water, Rotterdam is in the unique position of having two kinds of water available for export. The first is potable drinking water. The local water supply authority is the largest in the Netherlands. Every year 100 million $m^3$ of drinking water is produced. Even so, the capacity of the two production plants is only partially used. When working at full capacity, these plants can produce 15 million $m^3$ of drinking water per year for transport by tanker for many years in the future. This quantity would be sufficient to keep a town of 400,000 inhabitants supplied with drinking water.

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Facilities are already available in the port of Rotterdam for pumping drinking water aboard ship. At this moment, the loading capacity without storage is 2,000 $m^3$ per hour. By April 1986, this capacity will be increased to 4,000 $m^3$ per hour, and a loading capacity of 10,000 $m^3$ per hour would be quite feasible if intermediate storage is used.

The drinking water is produced from water derived from the River Meuse. This water is stored in three basins in the Biesbosch nature park, which have a combined delivery capacity of 250 million $m^3$ per year. Under good management, a natural pre-treatment takes place during the storage of the water for five to six months. Subsequently the water is brought to the production plants via a pipeline laid specially for this purpose. Rotterdam has at its disposal two ultra-modern production plants where the water is treated with the aid of the very latest techniques. The quality of the drinking water easily meets the requirements of the World Health Organization.

Rotterdam can also supply non-potable fresh water, since it is situated in the immediate vicinity of the Brielse Meer, a lake with a potential capacity of 300 million $m^3$ of fresh water every year. The water from the Brielse Meer has a low salt content and can therefore be used for agricultural purposes. Water from the lake will therefore be used for this purpose in the Netherlands too. To be able to achieve this, work has started on the construction of a pumping staton and the laying of a pipeline. Since this pipeline will run through the port area, it will be possible in due course to supply the ships with fresh water from it.

## 2. Systems of water transport

Water can be carried as ballast in segregated ballast tanks. In view of the developments taking place in the design of tankers, this will become increasingly feasible in the future. Water can also be carried as ballast in cargo tanks. A combination of the two is also possible.

Another possibility is that a vessel is used specifically for the transport of water and thus carries no cargo on one stretch of the journey. In this case, there can be said to be a shuttle, the water being carried in clean tanks. Both systems can be used for the transport of fresh water and drinking water. Hybrid systems could also be used in Rotterdam; for example, drinking water could be carried in segregated ballast tanks and fresh water from the Brielse Meer in cargo tanks.

## 3. Cost example of drinking water ballasting

As an example of water transport, the costs of carrying drinking water in the segregated ballast tanks of crude oil tankers on their return journey from Rotterdam to Ra's at Tannurah were calculated (figure 16). The water is assumed to be used for drinking or some other high quality use, for instance the replenishment of aquifers.

This example was chosen because the quantity of "clean" ballast tanks available is expected to increase as a result of the MARPOL convention so that it will be possible to carry considerable quantities of drinking water, which will not come into contact with oil, at low costs. The route in question was chosen because if offered good logistical opportunities.

The entire process from the purchase of the drinking water to the final consumer consists of the following steps:

- purchase of water
- loading (shifting, storage, pumping, delay)
- transport
- unloading (shifting, storage, pumping, delay)
- post-treatment
- (distribution)

In the following each of these stages is discussed, with the exception of distribution. There is nothing that can usefully be said about this since it will depend almost entirely on the local situation. All the costs which are referred to will be stated in the first instance as a proportion of the total costs of the drinking water including post-treatment. The latter treatment is necessary in order to raise the quality of the drinking water after the journey, since it may well have been in the tanks for a long period.

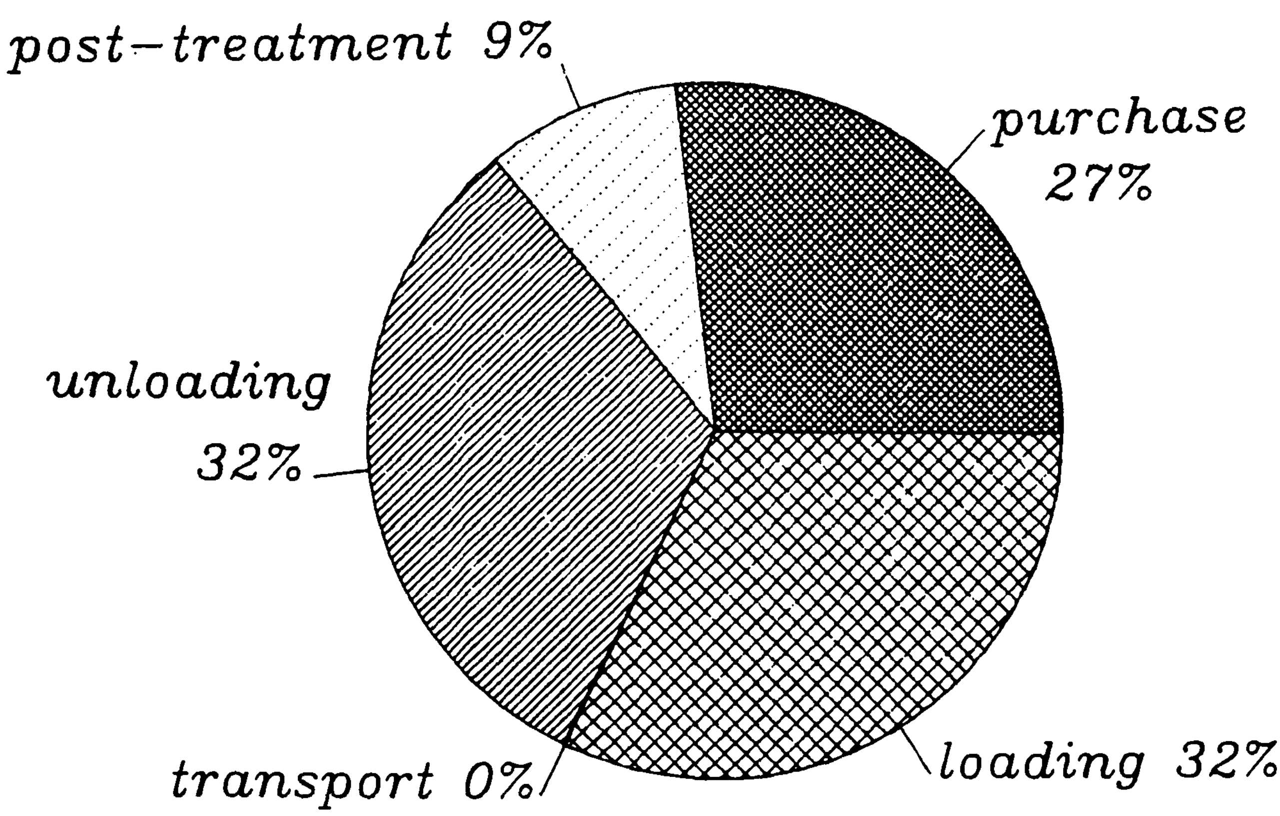


Figure 16. Components of total cost of drinking water transported from Rotterdam to Ra's at Tannurah (via Suez)

Purchase. In this case, the purchase price of drinking water accounts for 27 per cent of the total costs. It is the price which the major customers in Rotterdam pay for their drinking water.

Loading. The second item is the loading costs. These constitute 32 per cent of the total price. "Loading" includes the costs of items such as shifting, storage, pumping and delay.

The calculation of the loading costs is based on a loading capacity of 4,000 $m^3$ per hour, which will soon be available. Since this capacity could, with storage, be increased to 10,000 $m^3$ per hour, a tanker could be loaded with 80,000 to 90,000 $m^3$ of water in the space of ten hours.

Transport. If the tankers were used efficiently, the actual extra transport costs in the example would be negligible. The calculations are based solely on the minimum ballast needed for safe navigation (on average about 30 per cent of the loading capacity).

If more than this quantity is carried, sailing through the Suez Canal would often be uneconomic or even impossible because of the limited depth. This subject has been dealt with in detail by others. In the example the calculation is based on the tanker's most economic speed.

It is of course possible to deliver the drinking water to a country which is on the ship's route or close to it and then to continue on to the final destination. In that case the transport costs would be higher.

Unloading. The share of the costs of unloading in the total costs is the same as that of the costs of loading, i.e. 32 per cent. The process followed in loading is simply repeated in the unloading, but in the reverse order. It would not in fact be necessary to have facilities ashore for the storage of drinking water. One alternative would be to use a tanker for storage, either temporarily or otherwise. This could be an attractive option in view of the present overcapacity in the tanker fleets, and it would require only a small investment in comparative terms.

Post-treatment. Assuming that the drinking water is carried in segregated ballast tanks, all that is needed when it is delivered is a simple form of post-treatment. The costs involved are only 9 per cent of the total costs. The post-treatment also takes up little time, so that the drinking water can immediately be used for consumption or some other high quality purpose. After a simple treatment with chlorine bleaching lye, it meets the standards of the World Health Organization.

According to these estimates, the costs of a cubic metre of drinking water are between $US 2.00 and 2.50. For those costs it is possible to deliver drinking water which has never been in contact with oil. A drawback is that as matters stand at present in connection with the MARPOL convention, only a limited number of tankers are fitted with segregated ballast tanks. According to rough estimates, only 20 per cent of the tankers have such tanks.

This restricts the scope for delivery from Rotterdam using this method to a few million $m^3$ per year. The opportunities will be much greater in future because new tankers will be fitted with segregated ballast tanks.

The Appendix describes a method of treatment for use in cases in which larger quantities of drinking water are needed. In our view excellent drinking water can be made at an acceptable cost from drinking water which is slghtly polluted with oil. In addition, it should be emphasized that water which is polluted slightly with oil residues, can be used safely for many purposes in industry and agriculture. Slightly polluted drinking water can also be used to replenish the ground water by injection into the ground; through this process, it once again becomes fit for human consumption.

The costs of drinking water carried in cargo tanks are valued at US$ 2.50 to 3.00/$m^3$. This sum includes the costs of final treatment of the slightly polluted drinking water. The advantage of this transport system is that optimal use can be made of the logistical options.

For the sake of completeness, the costs of drinking water carried by shuttle and those of desalinated water should be mentioned too. The costs of water carried by shuttle transport under the same condition as those referred to in the example are valued at US$ 8.00 to 8.50/$m^3$.

The calculation is based on the fact that the tanker is owned by the recipient country and that the purchase price is low in view of the present overcapacity in the tanker fleets. Desalinating water by means of the Multi-Stage Flash Evaporation Method costs between US$ 4.50 and 8.00/$m^3$. Therefore, transport of drinking water in segregated and/or cargo tanks is competitive with desalination. Also a water shuttle should not be overlooked as an alternative.

## Conclusions

The transport of drinking water by tanker has never really been successful on a large scale, no matter what the method used. This is not explainable on the basis of economic considerations, however the relative figures quoted may look. The question is whether this will ever change in the future. The oil-producing countries have the means to transport drinking water by tanker. However, they prefer a method which keeps them self-sufficient in water. Other countries are quite willing to opt for the transport of drinking water by ship, but are unable to do so because of their lack of means.

The question arises whether it is realistic and responsible to view the problem solely from the financial point of view. In this connection we should like to quote Mr. Abel Wolman, the elder statesman of the drinking water industry in the United States, who assessed the progress made at midpoint in the International Drinking Water and Sanitation Decade:

"Economists have categorized water as an economic commodity that should always be subject to benefit-cost scrutiny. I do not share that view. People could well live without the telephone, the automobile, a destroyer. Without water, their survival is a matter of days. Cost-benefit seems unreal and singularly inappropriate."

## Appendix. The purification process of oil contaminated drinking water

Drinking water which has been in contact with crude oil for approximately three weeks is found to contain about 10 ppm aromatic compounds. The formation of stable emulsions does not appear to take place. A relatively easy purification of the water is possible. During the pumping of water ashore it is necessary to control the pumping to avoid the mixing of oil and water which have been separated during sailing.

The water is pumped into reservoirs or other means of storage.

To make the right choice out of the possible purification techniques a number of requirements can be formulated:

- after purification the drinking water must at the minimum satisfy the standards prescribed by the World Health Organization;

- because of reliability and experience, purification techniques which have proved themselves in practice must be used as much as possible;

- no environmental pollution may be produced;

- it must be possible to buffer fluctuations in supply;

- the purification process must run continuously;

- local facilities must be used as far as possible.

The costs can be limited by taking into account the following aspects:

- the purification techniques used must be acceptable and require little maintenance, requiring less skilled operating staff;

- the number and quantity of purification products supplied from elsewhere must be limited;

- with regard to the costs of earth moving, the use of wadis should be considered.

On the basis of the above requirements and considerations, two purification processes have been developed, using the results of the experiments already mentioned. The two processes are largely identical; the difference consists of the soil filtration which may be applied, depending on the local soil conditions. Figure 17 gives a block diagram of the two processes.

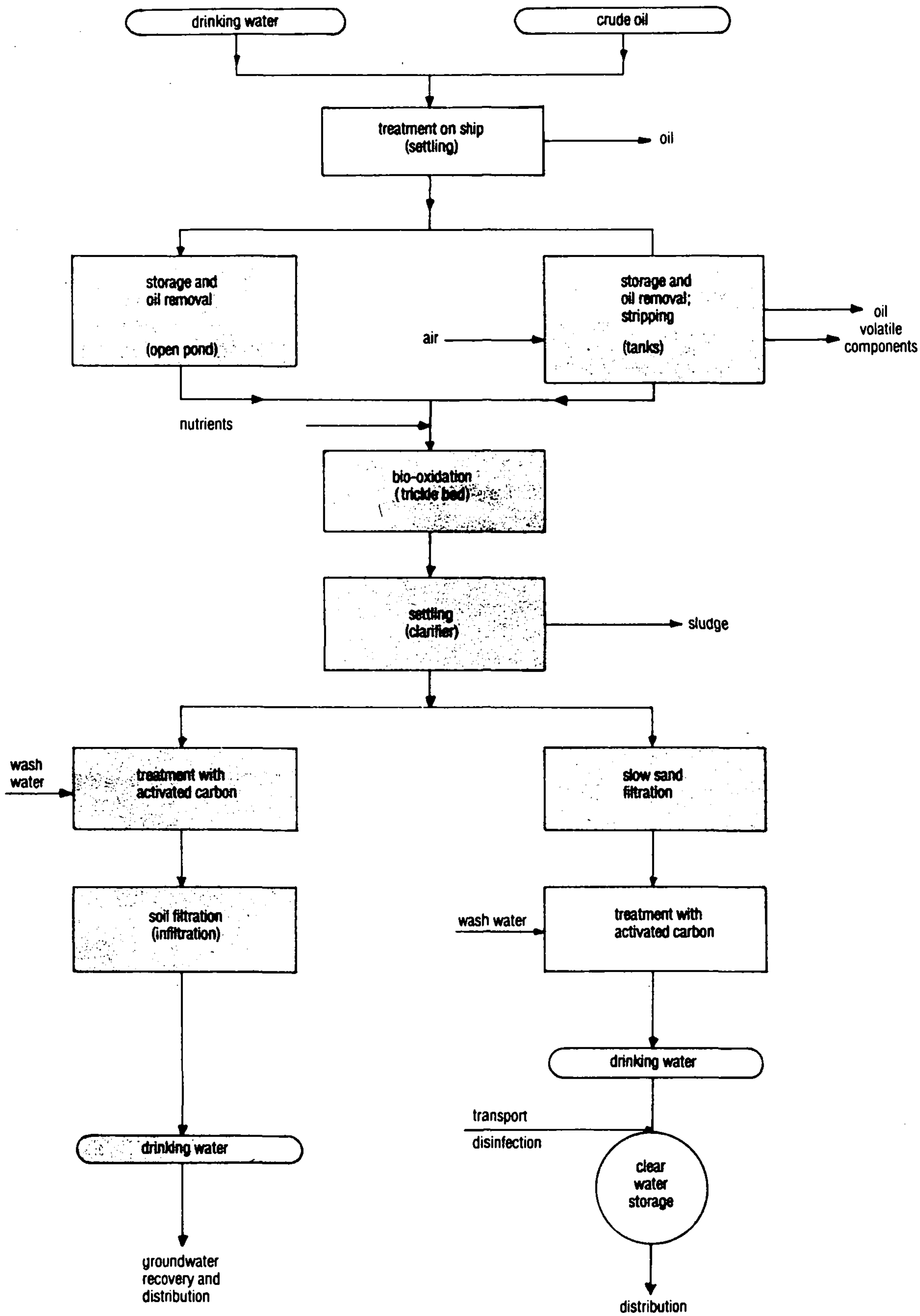


Figure 17. Block diagram of the water purification process

Figures 18 and 19 show visually how both of these look in practice. In the light of the figures, a brief description of the philosophy behind the selected processes will now be given.

Process without soil filtration. As shown in figure 18, the water transported is pumped ashore by the ship's pumps to the storage tanks.

Storage has a dual purpose:

- creating a buffer in case of discontinuous supplies;

- separating oil, bringing it to the surface and removing volatile components.

The buffer function is necessary to guarantee that the purification installation downstream can operate continuously.

As well as the normal pattern of supplies, allowance must be made for stagnation and excess supplies.

Aeration equipment can be fitted in the storage tanks, in order to remove the volatile components, speed up the oil separation process and increase the oxygen content.

The oil rising to the surface is returned to the ship via temporary storage. It will not be necessary to fit all the tanks with this equipment; the water transported in the clean ballast tanks can be stored in separate tanks.

After the storage phase comes purification in a trickle bed. This bed, made of coarse granular material, is where biological breakdown takes place. A slimy layer will form on top of the filler material, consisting of micro-organisms and organic material.

In the slimy layer, the dissolved and less volatile components are continuously broken down. The oxidized material will finally leave the trickle bed in the form of sludge. For the optimum control of this process nutrients also have to be added in the form of nitrogen and phosphorus, as oil forms too limited a source of food for the micro-organisms. Biological oxidation can be achieved in many ways; for example, oxidation ponds and active sludge installations are often used. In this case, however, the trickle bed has been chosen because of its good purification effect and the relatively simple plant management. In Europe a good deal of experience has been obtained with it, especially for treating household and oil-containing waste water.

The effluent from the trickle bed is transported to a clarifier to remove the sludge which has formed.

After the sludge has been tapped off, it can be transported to a sludge drying bed. The water at this point only contains very small suspended particles.

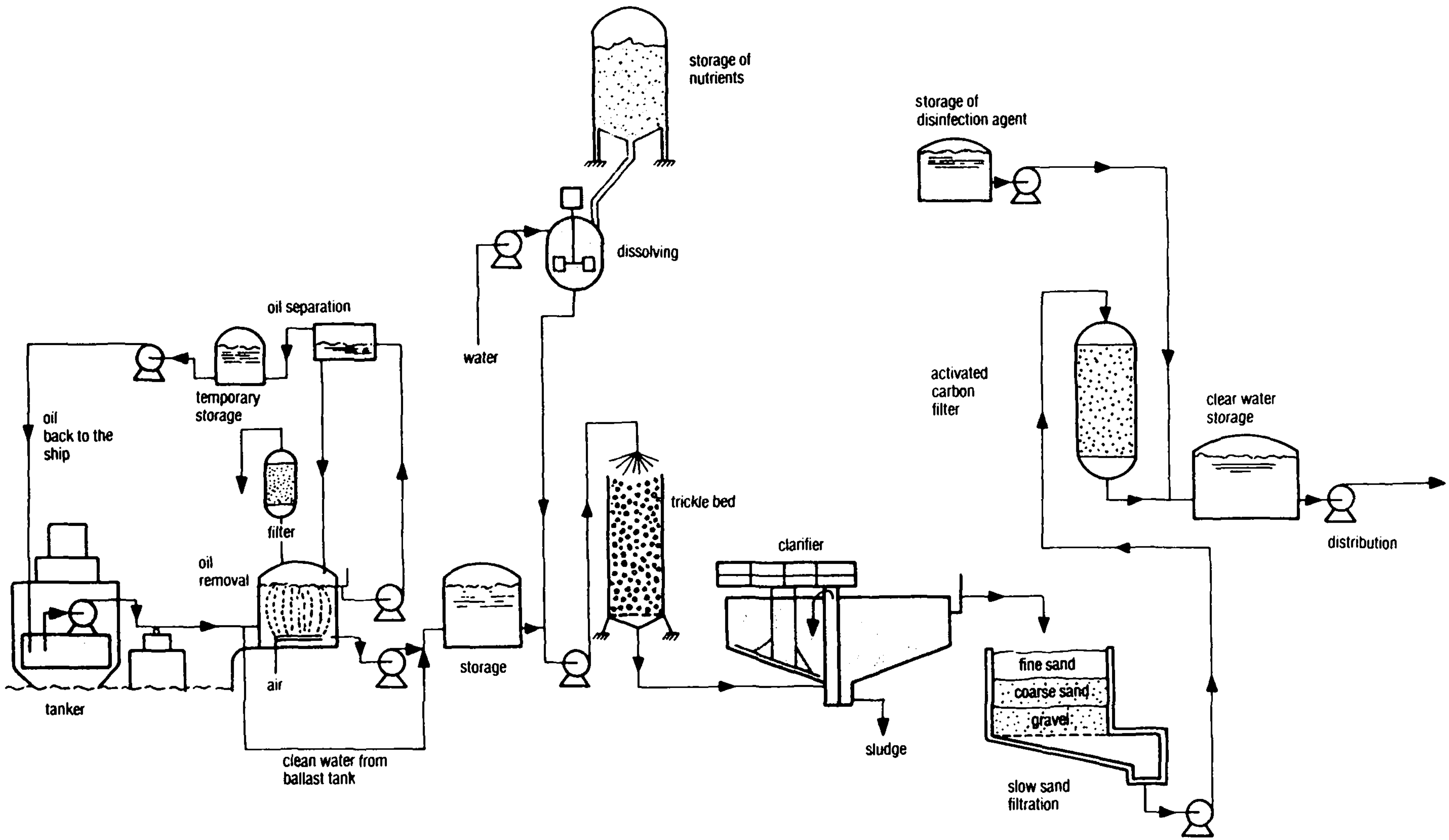


Figure 18. Water purification process without infiltration

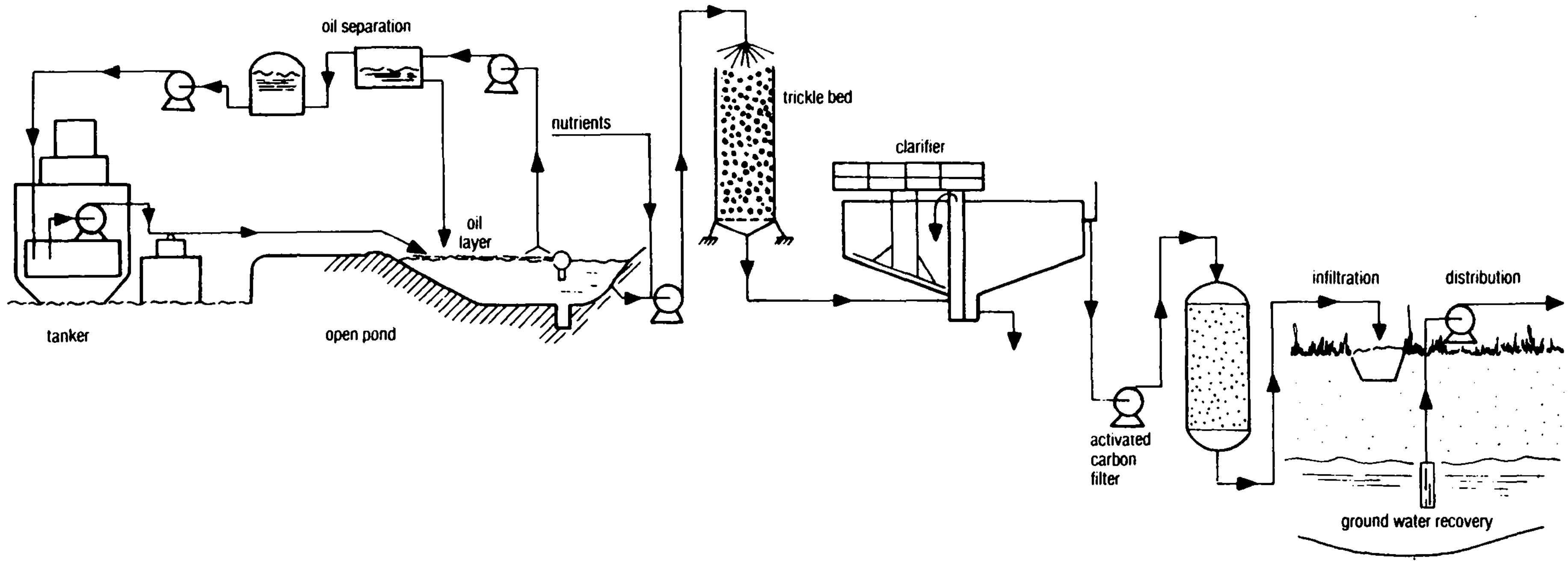


Figure 19. Water purification process with infiltration

In the slow sand filter mainly biological purification takes place. The remaining organic material is broken down and the result is clear water. This technique, which has been used for over a century, has a further important advantage: the effluent is hygienically reliable. This stage of purification is therefore called the main disinfection stage.

From time to time the top layer of the filter is scraped off to prevent blockage. After the sand has been washed it can be returned to the filter. To prevent pollution and the growth of algae, the slow sand filter is covered.

The choice for the last purification stage is an activated carbon filter. This filter, which provides a final clean up, has a polishing effect. The smell and taste of the water are improved and organic micro-impurities are absorbed. Thanks to the previous slow sand filtration, the pollution load is very low and the filter only needs to be regenerated and washed back at very long intervals.

Before the water is stored in the clear water reservoirs, transport disinfection must be applied to prevent the subsequent growth of bacteria. Hypochlorite solutions can be used for this purpose, which are simple to add. Very little is needed as the only purpose is to keep the water in the distribution system bacteriologically pure.

Process with soil filtration. When the geo-hydrological structure of the soil is suitable, infiltration can be used.

Before the water goes into the soil, a large part of the pollutants it contains must be removed. Pre-purification is therefore necessary. Two examples of infiltration are surface infiltration, using infiltration ponds, and deep infiltration assisted by wells. Which system is used will depend on local soil conditions.

The purificaton process with soil infiltration is not in principle any different from the previous process without infiltration. The series of purification stages have the same purpose; in the following, only the differences are therefore discussed.

When local conditions permit, an open pond can be created. This solution is considerably cheaper than using tanks and can therefore offset the evaporation losses which will occur with open storage. Oil separation can be carried out simply with floating skimming equipment.

Where necessary, the permeability of the soil can be reduced by fitting plastic sheeting.

Before the water is filtered, activated carbon filtration may be applied. The filter will be polluted rather more in this case than in the process without infiltration, but the filtration water will now be free of the last remains of substances spoiling the smell and taste. The advantage of this is that no real purification has to take place in the soil. What will occur is polishing as a result of biological activity and hygienically reliable water is obtained as a result of the long detention time.

There are a number of additional advantages linked with infiltration, such as:

- the temperature will be constantly kept as a low level;

- a very large storage can be formed;

- the water can be pumped up and used without any subsequent purification where and for whatever purpose one requires it.

# IV. WASTE-WATER REUSE

## A. Overview of water reuse for developing countries

by Jon DeBoer*

### 1. Background

Reuse of municipal waste water for beneficial purposes has been practised throughout the world for many years. Historically, evidence of planned direct reuse by the Romans in the first and second centuries A.D. attests to the fact that municipal waste water is a resource with an intrinsic value we cannot afford to disregard. Developments in Europe led to the installation of sewage farms in Germany in the 1500s. Other countries also have historical examples of water reuse. However, practical applications of water reuse require two key infrastructure investments for a modern developing country. Water supply must be provided with a relatively complete distribution system, and a water-carried waste disposal system must be planned or in place. Without these key ingredients, for example in rural, undeveloped areas, water reuse is not practical, and should not be considered.

For developing nations, a case could be presented for avoiding the installation of the commonly accepted and even sought after water-carried waste disposal systems. Sheaffer and Stevens, in their somewhat controversial book, Future Water (1983) condemn the highly touted sanitary engineering profession as a self-serving group of egotists unwilling to admit their linear water systems, e.g. "use it once and then throw it away", are the greatest municipal failure of all time. I cannot ascribe to their overall condemnation. However, alternative disposal techniques, especially for communities without existing waste-water systems, could at least be considered before blanket acceptance of the conventional system.

I do not, however, have the alternative solutions that will satisfy a growing commercial and industrial urban area. Therefore, for the purposes of this discussion, it is assumed that municipal wastes are handled by conventional water-carried systems and the high per capita use such systems demand.

In industrialized nations, this assumption is practical. In developing nations, the lack of centralized water-carried waste systems may provide the major barrier to practical municipal waste-water reuse developments. Even when a sewage collection system is present, many developing nations are faced with major problems in maintaining and operating such systems. Limitations on numbers of skilled operators, maintenance personnel and managers often mean only rudimentary systems may be provided. Also, lack of, or shortage of, replacement parts, chemicals and monitoring capabilities lead to inefficient operations.

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Notwithstanding all these limitations, systems are available that may provide developing countries with techniques to obtain benefits from waste-water reuse.

(a) Factors affecting water reuse

As briefly explained above, a source of reclaimable waste water must be available. Additional factors that would encourage waste-water reuse include:

(i) Shortage of fresh water of adequate quality to meet the minimum needs of the community;

(ii) Additional fresh-water supplies available only at excessively high costs;

(iii) Users with large demands for lower quality water located nearby;

(iv) Treatment techniques for rendering waste water sufficiently harmless available, practical, and reliable;

(v) Social and legal systems which do not bar the use of reclaimed waste water;

(vi) Cost of treatment and distribution acceptable.

When all the conditions for water reuse potential are present, increased utilization of this resource will occur. However, even in industrialized nations, the full potential is never realized. Table 27 shows water use and reuse in the United States. As this table indicates, the actual fraction diverted to beneficial reuse is very small, only about 8 per cent of the available municipal waste water.

Table 27. Summary of water reuse in the United States

| Category | Water use (million $m^3$/day) | | |
|---|---|---|---|
| | 1975 | 1985[a] | 2000[a] |
| Fresh-water withdrawals | 1373 | 1349 | 1253 |
| Municipal withdrawals | 100 | 115 | 140 |
| Municipal discharges | 81 | 90 | 104 |
| Industrial withdrawals | 531 | 485 | 377 |
| Industrial discharges | 503 | 460 | 282 |
| Municipal reuse | 3 | 8 | 18 |
| Industrial recycling | 526 | 1464 | 3276 |

Source: Adapted from Noyes Data Corporation, Wastewater Reuse and Recycling technology (Park Ridge, N.J., 1980).

a/ Estimates

As the demand for water increases within a developing country, the availability of a reclaimable waste water also increases. Other means of satisfying the increasing water requirements are available, and must be considered, especially from an economic point of view. However, waste-water reuse, developed in concert with sewage collecton and treatment, will aid in preventing contamination of existing water resources. In developing nations, preserving the quality of raw water sources may provide one of the most important benefits of a reclamation and reuse scheme.

(b) Definitions

The terminology used by professionals in the field of water reuse has been developed to fit a particular situation. In some cases the terminology may cause misunderstandings. This paper will use the following basic definitions:

Reclamation: the treatment of waste water (usually of a domestic origin) for beneficial use. The use may be man-made or natural, such as for fisheries and stream flow augmentation.

Reuse: the actual planned application of reclaimed waste water to a beneficial purpose. It may be direct reuse or indirect reuse, but does not include inadvertent and unplanned reuse, such as discharging waste water to water sources used downstream as a water supply resource.

Recycling: the reuse of waste water within a single water-using entity, such as an industrial complex. The recycling may be the reclamation and reuse of a mixed waste water flow from the entire source, or it may be a cascade reuse of an effluent from a single process stream for a second process with lower water quality requirements.

## 2. Current technology

The technology available for water reuse is a combination of existing waste-water treatment technology and water supply treatment technology, with the addition of some industrial treatment technologies. These technologies range from the most sophisticated and complex man-made processes available to some of the simplest, natural systems available to all. Obviously, each has its place in the realm of water reuse, but each also has economic and operator skill constraints. It is human nature to desire the newest and best, the flashiest or most respected technology available for our endeavors. We must all, however, remember our resources when choosing water reclamation and reuse as water sources. Planners, designers, engineers, managers, and operators must know their own limitations, and must keep in mind the limitations of the local situation when implementing reuse. A sophisticated, complex treatment and reuse system that fails to function properly is a disservice and waste of time and money if it has been installed without consideration of the resources available to the system owner.

(a) Conventional waste-water treatment

Whether domestic and other municipal waste is reused or is discharged to natural waters, the same treatment technologies are available to begin to reduce and/or eliminate the undesirable components of the waste stream. Table 28 shows typical domestic waste-water components of importance for water reuse, with removal and effluent concentrations when a typical municipal waste water is processed through several treatment schemes.

Table 28. Typical municipal waste-water characteristics

| Constituent | Concentration (mg/l) | | | |
|---|---|---|---|---|
| | Raw | Primary | Secondary | Tertiary |
| $BOD_5$ | 200 | 115 | 25 | 5 |
| COD | 400 | 250 | 100 | 50 |
| TOC | 100 | 65 | 15 | 10 |
| Suspended Solids (TSS) | 200 | 130 | 25 | 2 |
| Dissolved Solids (TDS) | 500 | 500 | 500 | 500 |
| $NH_3$-N | 20 | 16 | 6 | 4 |
| $NO_3$-N | 1 | 1 | 11 | 9 |
| TKN | 15 | 10 | 3 | 2 |
| Total Phosphorus | 10 | 7 | 4 | 2 |
| Heavy Metals | 1.8 | 1.0 | 0.3 | 0.3 |

These figures are typical averages. Specific processes used may alter specific removal capabilities, and therefore the concentrations found after treatment will vary from these averages. Secondary treatment assumes biological oxidation and final settling. Tertiary treatment for the purpose of this table is mixed media filtration.

Secondary waste treatment processes can be divided into two classes: low technology, low energy-intensive systems and high technology, energy-consumptive systems. The low technology systems include:

(i) Lagoons--aerobic, anaerobic facultative, or aerated;
(ii) Aquaculture;
(iii) Wetlands--artificial or natural;
(iv) Overland flow; and
(v) Slow rate land treatment.

Each of these systems provides a reasonably cost-effective approach to the removal of biodegradable material and the majority of solids found in typical municipal waste water. Preliminary treatment, including screening, grit removal, and primary sedimentation should be provided ahead of each system.

Overall removal efficiency of lagoon systems is generally lower than other secondary systems, often in the range of 60-70 per cent of biochemical oxygen demand after 5 days ($BOD_5$) and total suspended solids (TSS) removal.

This lower efficiency is due to the production of algae within the system cells, not the lack of removal of original solids and organics. Threrefore, this effluent may be very acceptable for certain water reuse systems. Design parameters are readily available from numerous sanitary engineering texts and handbooks.

A unique system for eliminating algal problems in lagoon systems has been proposed by Willis (1985) for a small community in the United States. The treatment system consists of a series of three aerobic ponds with very slow sand filters between cells. The filters, shown in figure 20 form an integral part of the pond embankment. Flow velocity at the face and within the filter is maintained below the settling rate of suspended solids to prevent blinding or clogging of the filter surface. This system has not yet been installed, so the success of this approach has yet to be proven in a full scale system. However, if it is successful, it may provide a very low cost solution to excess solids in lagoon systems.

Aquaculture systems for water reuse are generally based on the provision of constructed ponds, seeded with floating aquatic macrophytes (usually water hyacinth), various invertebrates, and often species of fish. Research has shown that optimum treatment occurs in ponds of sufficient depth to produce an anaerobic layer at the bottom of the pond (Reddy, 1985). Supplemental aeration is sometimes provided to maintain adequate oxygen in the upper layer, but this greatly increases the complexity of a simple system.

Removal of contaminants of concern have been shown to be quite good. Table 29 shows the influent, first stage effluent and final effluent from a pilot plant aquaculture system (20,000 gpd) (Conn and Langworthy, 1985). DeBusk and Ryther (1985) have shown the importance of harvesting the standing crop of hyacinth when using aquaculture for enhanced nutrient removal. However, the optimum harvesting rate for aquaculture systems has not been fully defined. The rate is site specific, and depends on the raw waste-water characteristics and the desired final effluent quality. Harvested hyacinth can be utilized as a livestock feed supplement, or may be composted to form a soil amendment.

Wetlands treatment systems of both natural and constructed designs have been implemented throughout the world, in both temperate and tropical climates. Operational characteristics are generally held close to natural marsh, swamp, and wetlands conditions, with extraneous natural flows diverted, if possible. Plant species used include the full range of wetland species, including cypress trees on one hand and duckweed on the other. Most typical wetland projects in the United States rely on grasses, cattails, bullrushes, and similar rapid recovery systems. Raw water should be treated with a primary system to eliminate gross solids, unless the wetland system is specifically designed to handle raw waste water.

Hydraulic control of a wetland system is essential for effective treatment. Control can be designed into the system, alleviating much of the need for skilled operators. When using natural wetlands, however, hydraulic control may be more difficult and may require a sophisticated operational programme.

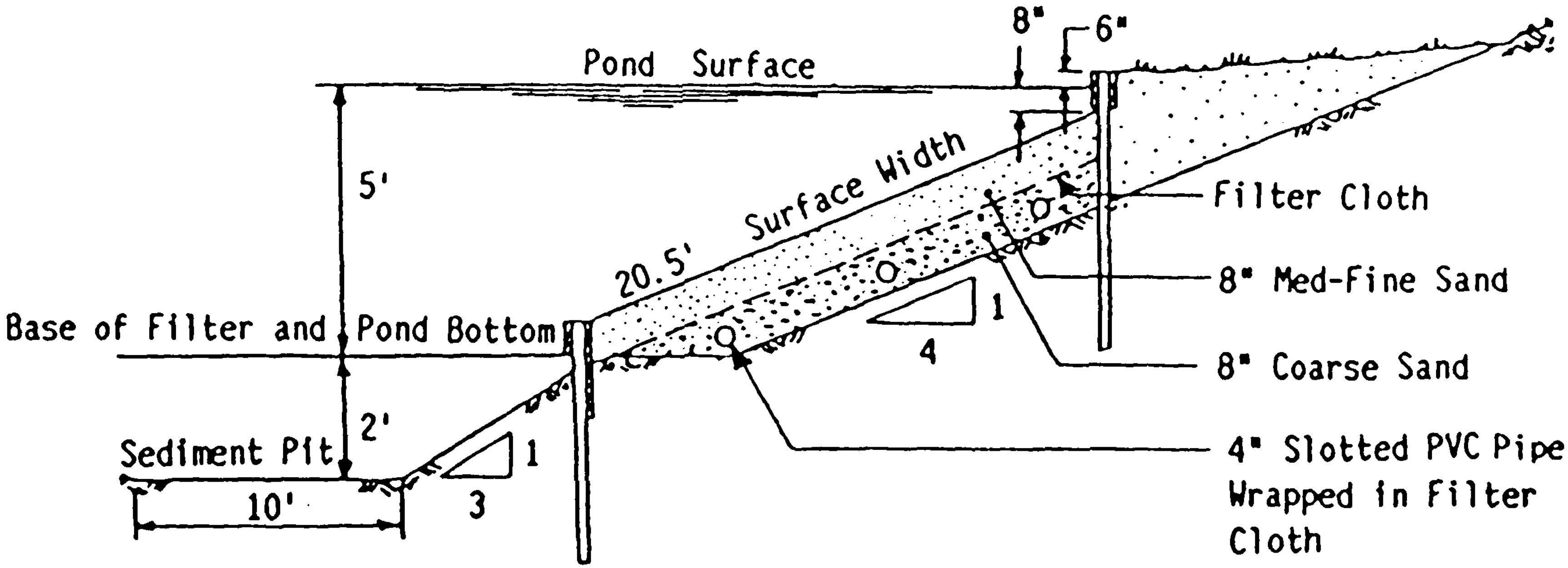


Figure 20. Very slow sand filter

Table 29. Typical aquaculture treatment efficiency

| | Screened Sewage | Initial Aquaculture Tank Effluent | Final Aquaculture Tank Effluent |
|---|---|---|---|
| Suspended Solids (mg/l) | 200 | 8 | 4 |
| $BOD_5$ (mg/l) | 150 | 29 | 19 |
| TKN (mg/l) | 41.9 | 36.0 | 9.4 |
| $NH_3$-N (mg/l) | 17.7 | 15.4 | 4.29 |
| $NO_3$-N (mg/l) | BDL | 2.46 | 6.35 |
| $TPO_4$ (mg/l) | 5.0 | 4.3 | 4.3 |
| COD (mg/l) | 381 | 58 | 46 |
| TDS (mg/l) | 821 | 817 | 817 |
| Turbidity (NTU) | 39 | 17 | 6.0 |
| Colour (units) | 54 | 37 | 34 |
| Hardness as $CaCO_3$ (mg/l) | 271 | 273 | 273 |
| Coliform (min/100 ml) | $130 \times 10^5$ | $49 \times 10^4$ | $33 \times 10^3$ |

Water must be uniformly distributed throughout the wetland. The wetland treatment system relies on the vegetation present for a high percentage of the treatment that occurs. Therefore, these water-dependent species must not be deprived if the waste-water source is intermittent. Drought conditions or other causes of a lack of waste water could kill the majority of the standing crops of a wetland, thereby requiring an extremely long recovery period before effective treatment resumes.

Typically, wetlands are loaded at the rate of 1-2 gals/$ft^2$/day with a detention time of 6-10 days. Effluent $BOD_5$ can be expected in the range of 10-30 mg/l.

Overland flow systems are similar to constructed wetlands with the exception that the depth of flow is a thin sheet of water rather than several inches to 1.5 feet as found in wetlands, and detention times are usually only 1 to 2 hours. Crops such as grasses that can thrive under high moisture conditions and have long growing seasons provide the most efficient overland flow system.

Water is distributed by sprinkler or gated pipe over the upper portion of a slope of 100-200 feet in length. Slopes must be uniform and steep enough to prevent ponding, but shallow enough to prevent erosion. Experience has shown that 2 to 8 degree slopes, depending on the soil characteristics, are generally satisfactory. Soils should be relatively impermeable, or the system becomes one of slow rate infiltration treatment, and underdrains then are required if reuse is to be practised. In overland flow systems, the effluent is collected at the toe of the slope, and is generally acceptable for many reuse applications without further treatment.

Recent developments in relatively low technology systems include the nutrient film treatment techniques (NFT). This technique is essentially thin film hydroponic crop production. A modification, termed gravel bed hydroponics is essentially the same as NFT, but includes the addition of a gravel layer to support the root mass and prevent channelling and erosion in the bottom of a water-impermeable channel or bed. The system may utilize a nutrient feed solution derived from pristine water with added artificial nutrients or highly treated waste water or even minimally treated raw water.

A study by Handley and others (1985) in southern Florida was designed to prove this technology as a viable treatment technique for tropical developing countries. Tropical wetland forage grasses were chosen for this study, including paragrass and napier grass.

In addition, torpedo grass was tested, but did not survive under the conditions of nutrient film treatment using raw sewage or secondary effluent. Other researchers have demonstrated that garden crops can be economically grown on secondary effluent using NFT. Handley suggests further research in this area, using forage crops for the first stage and cash garden crops for the second stage or polishing system. Final effluent would then still be reusable for various urban or agricultural uses.

High technology conventional waste-water treatment systems include:

(i) Activated Sludge;
(ii) Trickling filters; and
(iii) Rotating Biological Contactors.

In addition, wide variations of these three standard systems exist. Oxidation ditches, pure oxygen activated sludge, and powdered carbon activated sludge are only a few examples of these process variations. Additional process units, such as separate basins for nitrification/denitrification, addition of chemicals to enhance solids removal, and biological activity, as well as other changes, make the full range of treatment available much too diverse to discuss thoroughly in this one paper. Texts are available that provide background information and design data for all these unit processes.

However, one system variation should be mentioned that has been applied to water reuse in the United States. It is the activated carbon/activated sludge system. This system, patented in the United States as the PACT system may be combined with additional treatment processes to form an integral part of a reuse system producing highly polished water. This system is shown in figure 21.

Powdered activated carbon (PAC) is added following activated sludge treatment and clarification. This slurry is then aerated in a denitrification system for both nitrogen removal and adsorption of residual organics.

Reclaimed carbon is returned to the first aeration stage for additional adsorption and to provide higher solids concentraton and a large surface area for suspended biological growth.

Following this biological treatment, additional physical/chemical treatment is provided by lime coagulation (with recarbonation), rapid sand filtration, disinfection, and granular activated carbon contact. The entire treatment system is currently being installed in a south-western United States city, where the treated effluent will be injected into the ground-water aquifer providing the potable supply source for the community.

(b) Advanced waste-water treatment

For water reuse systems where public contact or exposure is allowed, or which will be used for certain human food crops or, in the extreme, will be consumed as a potable water supply, additional treatment will be necessary. Two types of waste-water treatment are included here, namely:

(i) Nutrient Removal, and
(ii) Enhanced Solids Removal.

Nutrient removal is obviously of little interest when an effluent is to be reused for irrigation since the nutrients are a valuable asset for the crops, but for indirect or direct potable reuse, recreational reuse and perhaps some industrial uses, nutrients can present a nuisance or a problem. Phosphorus removal is often difficult without resorting to chemical precipitation, such as high lime coagulation. Natural systems frequently cannot remove the high phosphorus concentrations found in most municipal waste waters, since vegetation phosphorus requirements are only 10 per cent of their nitrogen requirements, but the phosphorus concentration of waste water is 20 per cent of the nitrogen concentration (or greater). However, lime precipitation is very successful in removing phosphorus.

Nitrogen, on the other hand, is more easily removed by natural systems, microbiological nitrification/denitrification or ion exchange for ammonia removal. Each of these treatment processes may be used as appropriate, depending on the waste-water quality characteristics and the sophistication of the overall system design.

Enhanced solids removal, the second area of advanced waste-water treatment, is a subject that has been misunderstood for many years. Often designers and operators have in the past proceeded on the basis of water supply filtration, only to meet with inefficient or failed systems. Young (1985) describes the general problems usually found, and provides a list of recommendations for solving many waste-water filtration problems. Proper initial design, and adequate backwash procedures are the backbone of his recommendations. Rigby (1985) studied a new (and patented) filter design termed the pulsed bed filter in a side-by-side comparison with dual media filtration of secondary effluent intended for reuse. Both filter systems are effective for meeting stringent water quality standards, although turbidity and bacterial removal of the pulsed bed filter was somewhat better than dual media.

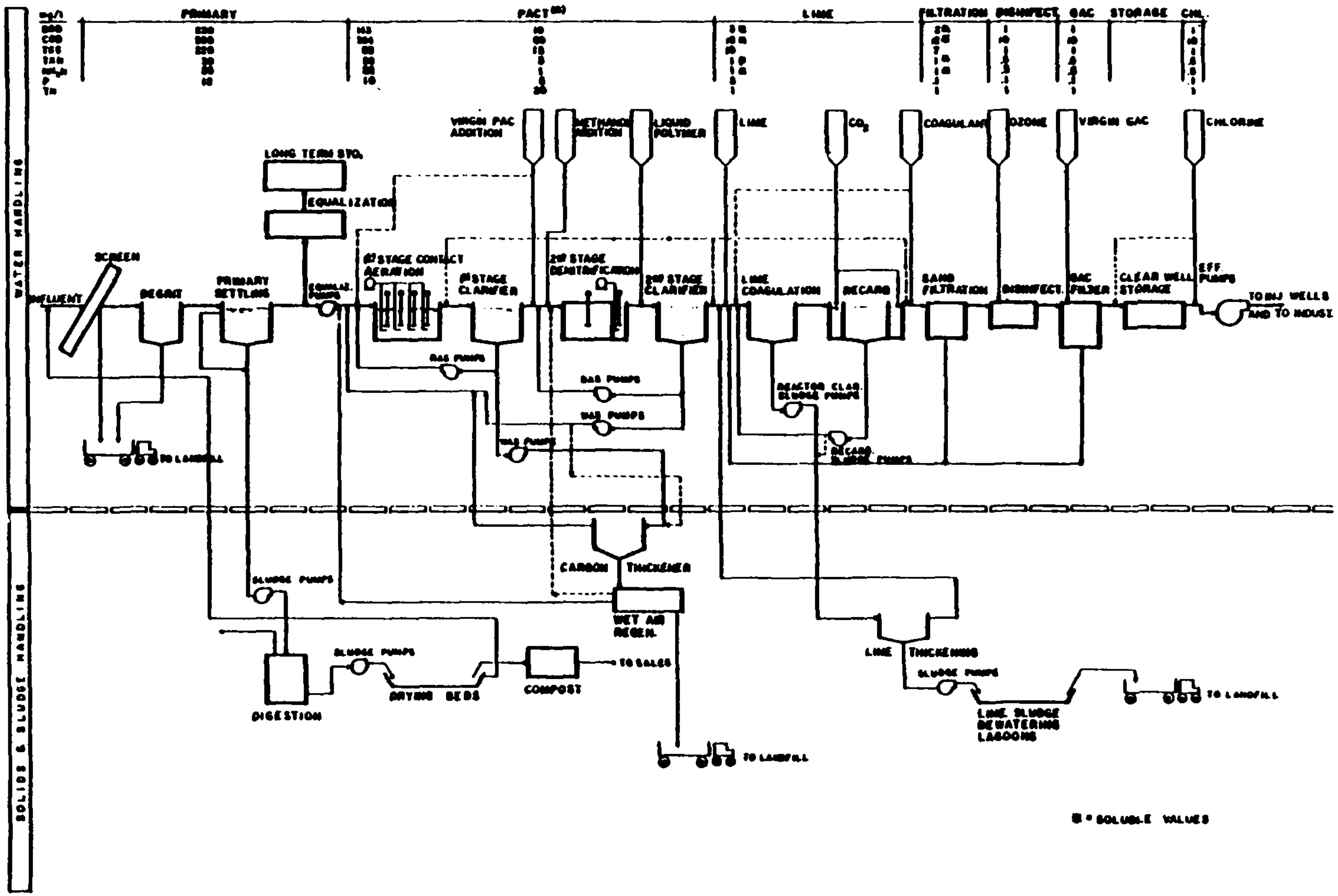


Figure 21. PACT Treatment Process Design

The pulsed bed filter is similar to a conventional water filter, although the sand depth is only 10-12 inches. The pulsed filter is shown in figure 22. Sensors above the bed operate the various cycles automatically. Following backwash, the filter is drained to the sand surface, at which time waste water is introduced. When head loss reaches a few inches, the first water level sensor initiates an air mix. A diffuser introduces air immediately above the sand surface, keeping large floc particles in suspension and preventing a "blinding" effect of the sand surface. Once head loss reaches about one foot, the pulse mix sensor begins the periodic "bumping" of the entire filter bed, accomplished by the introduction of air through the underdrain. The final backwash sensor repeats the entire cycle.

In addition to filtration, other treatment techniques for enhanced solids removal include the use of wetlands systems or aquaculture as "tertiary" treatment units. Ground-water passage is also a very effective treatment technique for polishing secondary effluent. The system can utilize high rate infiltration basins, land spreading, or dune or bank filtration. Water recovery can be immediate, through a series of interceptor drains, or the water may be stored in ground water aquifers for later recovery and reuse. With storage systems, special precautions to avoid contamination of existing high quality aquifers must be taken.

(c) Conventional water treatment

The unit processes utilized in conventional water treatment may be used to polish treated effluent for reuse. The processes have been practised nearly unchanged for decades, although continuing minor modifications and the introduction of new chemicals have optimized all the unit processes. The basic processes consist of:

(i) Solids Removal (coagulation/flocculation/sedementation),
(ii) Softening,
(iii) *Filtration,*
(iv) Disinfection.

Descriptions of these processes, including all the variations possible are available in many texts, and will not be re-examined here. It is sufficient to say that the influent water to these processes must resemble natural raw waters for the processes to be operated efficiently. For example, high concentrations of biodegradable solids will interfere with filtraton, cause putrescent sludges, anaerobic conditions, and require higher disinfectant doses. Preliminary treatment through conventional and enhanced waste-water treatment processes is necessary to ensure optimal final treatment.

(d) Enhanced water treatment

Obviously, many reuse applications will not require treatment beyond secondary waste-water treatment or perhaps secondary treatment plus filtration. However, for those uses that demand high quality water, additional treatment may be required. In reuse, these additional processes include:

(i) Ion exchange,
(ii) Desalination,
(iii) Adsorption, and
(iv) Oxidation.

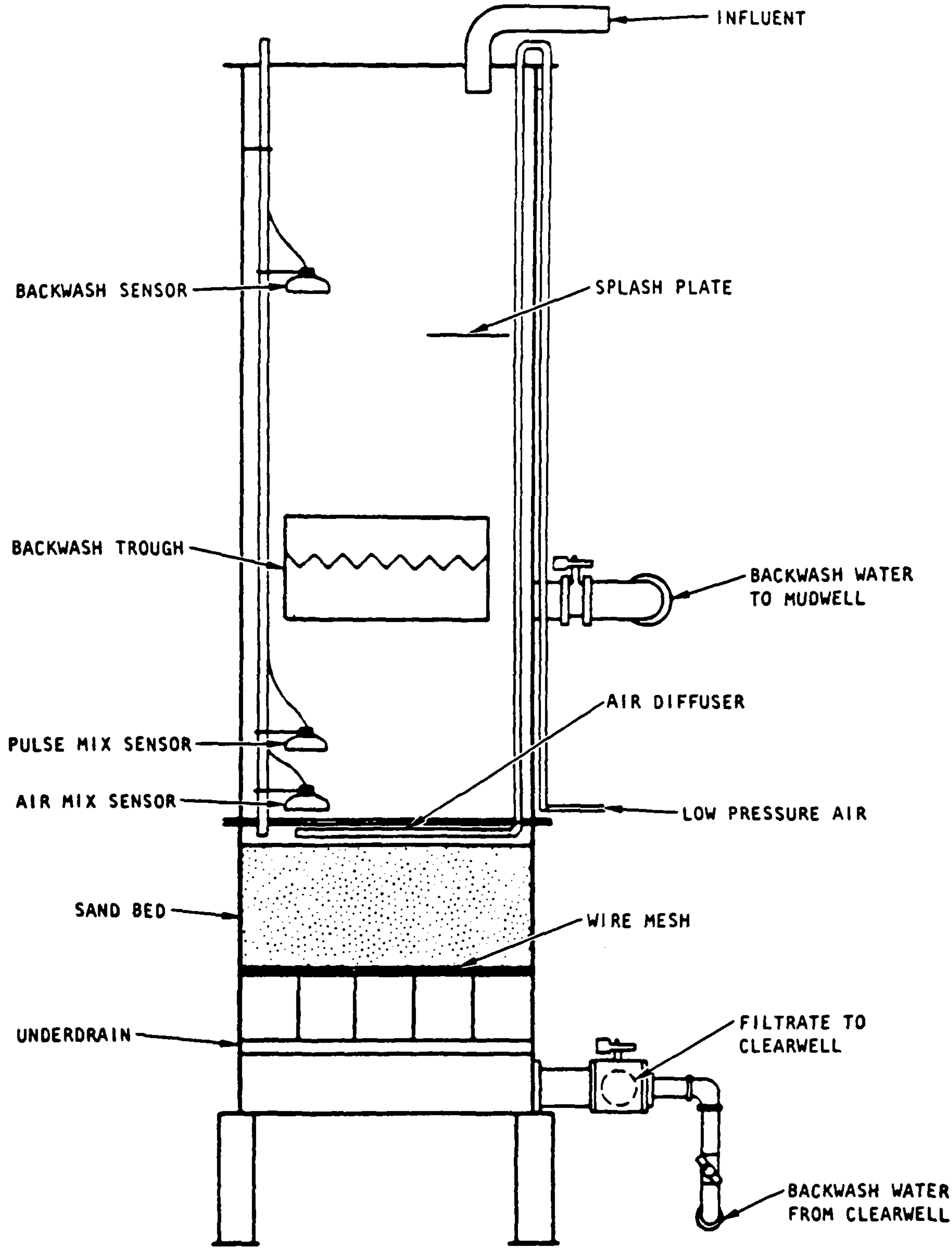


Figure 22. Cross section through pulsed pilot filter

Ion exchange can be used for the removal of specific ions from water, in addition to the more usual purpose of softening. In reuse, ion exchange is frequently used for ammonia nitrogen removal. A recovery process has been developed where the ammonia is reclaimed as ammonium sulphate, a valuable fertilizer. In industrial reuse, ion exchange can reclaim heavy metals and can be used in separate anion/cation exchangers for desalination. Other desalination systems are also applicable to water reuse systems, either for industrial reuse and recycling, or for reducing the salt buildup from municipal use. Systems for desalination include:

(i) Reverse Osmosis,
(ii) Electrodialysis,
(iii) Distillation, and
(iv) Ultrafiltration.

These processes are fully described in papers discussing the use of sea water or brackish water. The same processes are employed in water reuse systems, so it would be redundant to present detailed discussions here.

Adsorption processes include activated carbon and a variety of synthetic resins. Resins are generally more expensive, and for municipal reuse, granular actived carbon (GAC) has become the treatment of choice for most applications. Adsorption on carbon will remove many organic compounds, including many of health concern. GAC is a renewable process, through thermal reactivation, but the process is energy intensive, and therefore, quite expensive.

(e) Technology in distribution and storage

Dual distribution systems, supplying potable water through a primary system, and a lower quality, reclaimed waste water through a secondary system, have been employed at many sites in the United States. Uses for the secondary water include industrial supply, urban irrigation, and fire-fighting water. This type of solution to shortages of potable quality water can provide many benefits to a community. However, the system is not without penalties, including the following:

(i) Cost: while the primary piping and pumping system can be reduced in size, this does not off-set the additional cost of the secondary system.

(ii) Primary System Protection: since reclaimed water has the potential to contain harmful agents, the primary system must be protected from cross connections and contamination from leakage from the secondary system.

(iii) Management: from billing to service, the problems of management are nearly doubled with all dual systems.

Handbooks are available that provide guidance to designers and system owners when considering dual systems. Some, such as the American Water Works Association (AWWA) Dual Water Systems Manual (1983), contain information on modelling and cost estimation to assist in the decision-making process.

Storage technology for reuse systems is nearly identical to other conventional water and waste-water systems. Containment, restricted access, pressure considerations, etc., must all be accounted for. However, storage management is often unique for reuse systems. First, storage of unacceptable water must be considered to provide for the possibility of treatment failure. Water that does not meet the quality criteria established will require retreatment or alternative discharge, and storage will be necessary. Secondly, reuse supply and reuse demand do not always coincide, making storage of acceptable reclaimed water necessary also.

Often ground-water storage can reduce costs for this second storage need, while providing additional treatment through natural processes. The cost of re-extraction, as well as the cost of safeguarding potable aquifers must be considered when a ground-water aquifer is used as a storage reservoir.

### 3. Health effect implications of reuse

Other papers discuss the details of health effects of water reuse, but it is necessary to describe here several important aspects recently investigated in the United States and elsewhere, beginning with the most stringent conditions - direct potable reuse.

Two studies, one completed and one only just beginning, have examined direct potable reuse applications. For the Washington, DC metropolitan area, a pilot plant study examined the health implications of using municipal effluent as a major portion of the area's water supply. Limited to Ames test bioassays, the health effect study found that an extensive treatment scheme produced a water similar in mutagenic properties to the conventional water sources. The second study, beginning in Denver, Colorado will study health effects of water treated through the treatment scheme shown in figure 23. This study will examine the mutagenic and carcinogenic properties of the final product, and compare it to the existing water sources. If it is found acceptable, up to 15 per cent of Denver's water supply could be reclaimed water in the future.

In Cape Town, South Africa, an epidemiology study is under way to provide a baseline for the future, when it is anticipated that potable reuse could be implemented.

A number of systems in the United States are using, or planning to use, reclaimed water for indirect potable reuse. A health effects study performed in Los Angeles, California (Nellor, Baird and Smith, 1984) where ground water was recharged with reclaimed municipal waste water (in combination with captured urban runoff and natural stream flows) found interesting results. Analytical results and an epidemiologic study showed that while some compounds of concern were present in ground water consisting of up to 25 per cent recharged water, no adverse health effects were noted in those persons consuming that water. Interestingly, the captured urban runoff was frequently of poorer quality than the reclaimed waste water.

Health effects are also a concern when reclaimed waste water is used for non-potable purposes, such as agricultural irrigation, urban irrigation or

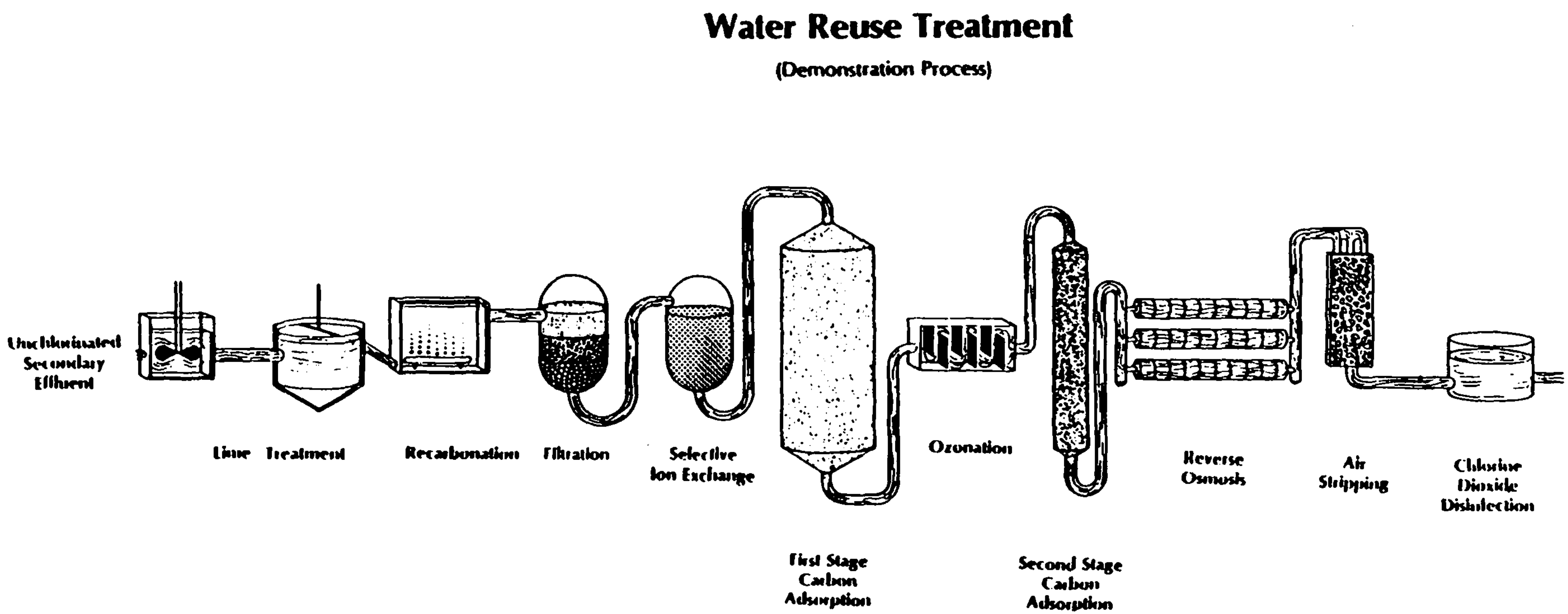


Figure 23. Water reuse treatment

industrial applications. Human exposure, through ingestion, inhalation or body contact can result from:

(a) Accidental drinking of reclaimed water;

(b) Exposure to sprays or aerosols near cooling towers and spray irrigation distributors;

(c) Working with reclaimed waste water;

(d) Eating raw food crops grown with reclaimed waste water;

(e) Body contact or inadvertent ingestion at recreation sites using reclaimed waste water.

The duration and degree of exposure are not as intense in these non-potable contacts with reclaimed waste water, but the safeguards and barriers to exposure are also frequently reduced. The risks become centred on acute hazards rather than chronic illnesses, so basic protection must still be provided.

## 4. Treatment requirements and costs

Treatment requirements for various reuse applications are based somewhat on the local conditions, including public health regulations. In the United States, requirements for reuse are established by state regulation, as no national guidelines or criteria have been set (with the exception of stream discharge requirements and drinking water quality criteria). A generalized composite of basic requirements is shown in table 30. These treatment levels may be considered an average of the various minimum requirements. Disinfection is included in all processes.

Costs for these processes are shown in table 31. These figures are in estimated 1985 dollars. Local conditions can greatly influence construction, equipment and materials costs, however, so care should be taken when using this table. Treatment levels assume preliminary screening and primary treatment preceding each process. Advanced treatment systems include secondary treatment costs.

## 4. Conclusions

The use of water reclamation and reuse schemes as additional water resources continues to increase throughout the world, both in water-short areas, and in areas with plentiful rainfall. In developing countries, the application of water reuse will often be precluded by less costly alternatives. However, in extremely arid areas, island nations with limited water storage potential and areas where alternative water costs are high, water reuse can be relied on to meet the needs of a growing, urbanizing community.

An economic analysis of the true cost of water reuse and all other water resources must be performed to evaluate the most appropriate resource development.

Table 30. Levels of treatment for various beneficial uses

| Beneficial use | Treatment levels |
|---|---|
| Agricultural irrigation - forage crops | Secondary |
| Agricultural irrigation - truck crops | Secondary |
| Urban irrigation - Landscape | Secondary plus filtration |
| Livestock and wildlife watering | Secondary |
| Power plant and industrial cooling | |
| Once-through | Secondary |
| Recirculation | Tertiary with lime ppt. and/or ion exchange |
| Industrial boiler make-up, low pressure | Tertiary with lime ppt. and/or ion exchange |
| Industrial boiler make-up, intermediate pressure | Tertiary with lime ppt. and/or ion exchange |
| Industrial water supply | |
| Petroleum and coal products | Secondary with nitrification and filtration |
| Primary metals | Secondary |
| Paper and allied products | Tertiary with lime ppt. and/or carbon adsorption |
| Chemicals and allied products | Tertiary with filtration, carbon, lime and/or RO |
| Food and kindred products | Tertiary with filtration, carbon, lime and/or RO |
| Fisheries | Tertiary with nutrient removal |
| Recreation | |
| Secondary contact | Secondary plus filtration |
| Primary contact | Tertiary with nutrient removal |
| Public water supply | |
| Ground water, spreading | Secondary (plus carbon adsorption) |
| Ground water, injection | Secondary plus filtration, carbon adsorption and RO |
| Surface water | Tertiary with lime, filtration, carbon adsorption and nutrient removal |

Table 31. Treatment process costs

| Treatment level | Treatment process description | Unit costs (US$/1,000 gal) | | |
|---|---|---|---|---|
| | | 1 mgd | 10 mgd | 50 mgd |
| 1a | Activated sludge | 1.60 | 1.10 | 0.66 |
| 1b | Trickling filter | 1.74 | 0.88 | 0.66 |
| 1c | Rotating biological contactor | 1.79 | 1.08 | 0.93 |
| 2a | 2-stage nitrification | 2.18 | 0.98 | 0.74 |
| 2b | RBC - nitrification | 2.37 | 1.64 | 1.42 |
| 2c | Oxidation ditch | 0.72 | 0.47 | * |
| 3a | Nitrification-denitrification | 2.50 | 1.21 | 0.93 |
| 3b | Selective ion-exchange | 3.15 | 1.49 | 1.08 |
| 4 | Filtration | 2.21 | 0.91 | 0.71 |
| 5a | Alum addition | 2.86 | 1.16 | 0.95 |
| 5b | Ferric chloride in primary | 2.59 | 1.28 | 0.96 |
| 5c | Tertiary lime | 3.26 | 1.35 | 0.99 |
| 6a | Tertiary lime, nitrification | 3.60 | 1.38 | 1.01 |
| 6b | Tertiary lime, ion exchange | 3.74 | 1.80 | 1.28 |
| 7 | Carbon adsorption, filtration | 2.94 | 1.20 | 0.95 |
| 8 | Carbon, lime | 3.97 | 1.65 | 1.23 |
| 9 | Carbon, lime, nitrification | 4.39 | 1.66 | 1.25 |
| 10 | Carbon, lime, ion exchange | 4.80 | 2.10 | 1.52 |
| 11 | RO, AWT | 8.00 | 3.57 | 2.86 |
| 12a** | Physical, chemical, lime | 4.16 | 1.71 | 1.34 |
| 12b** | PCT, ferric chloride | 4.26 | 1.92 | 1.44 |
| 13a** | Irrigation | 1.32 | 1.02 | 0.88 |
| 13b** | Infiltration-percolation | 0.63 | 0.32 | 0.26 |
| 13c** | Overland flow | 0.86 | 0.59 | 0.50 |

Notes:

* Not appropriate to large sizes

**Note that levels 12 and 13 are alternatives to biological processes and do not reflect higher levels of effluent quality.

Costs estimated in 1985 US dollars.

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## B. Waste-water reuse and its applications in Western Asia

by C. Ertuna*

### 1. Introduction

In view of the limited water resources of some of the member states of the United Nations Economic and Social Commission for Western Asia (ESCWA) region,1/ augmenting the conventional water supplies by non-conventional water development techniques has become a concern in the area (map 1). In addition, the idea of reuse of water by renovating and recycling waste water from municipal, agricultural and indusrial effluents is gaining increasing support in many other countries in the world. Alhough some people have objections to the prospect of getting treated waste water through their taps, very little aversion has been manifested against the use of treated effluents in industry and agriculture. Current technology has made it possible to treat the waste water and bring it to a quality level, with a few exceptions, equal to that of high quality natural water resources. However, the cost of such advanced treatment is high, and the general opinion is against the use of recycled waste water for domestic purposes. In consideration of the cost and of public opinion, the study on which this paper is based was designed to deal with the augmentation of only the agricultural and industrial water supplies through recycling water in the region.

The importance of waste-water reuse was recognized in the ESCWA region quite some time ago. As early as the 1950s, in Qatar treated effluents were used for irrigating municipal areas. The reuse of waste water was then put into application in Kuwait in a restricted manner, to be followed by the United Arab Emirates and Saudi Arabia. Today, this non-conventional method of water supply is in practice on a limited scale in Egypt, and there are plans to use treated waste water in irrigated agriculture in Bahrain. Jordan is considering treating municipal effluents from Amman and returning them to the King Tallal Dam for reuse. In Iraq, two sewage treatment plants near Baghdad treat municipal effluents before they are discharged to the Tigris for reuse downstream. Some conventions and techniques have been developed and experiences gained in the region. Some cost figures are also available. Although the health aspects of water reuse are not completely defined yet, experience has shown that confining the use to purposes other than domestic provides a fairly safe supply.

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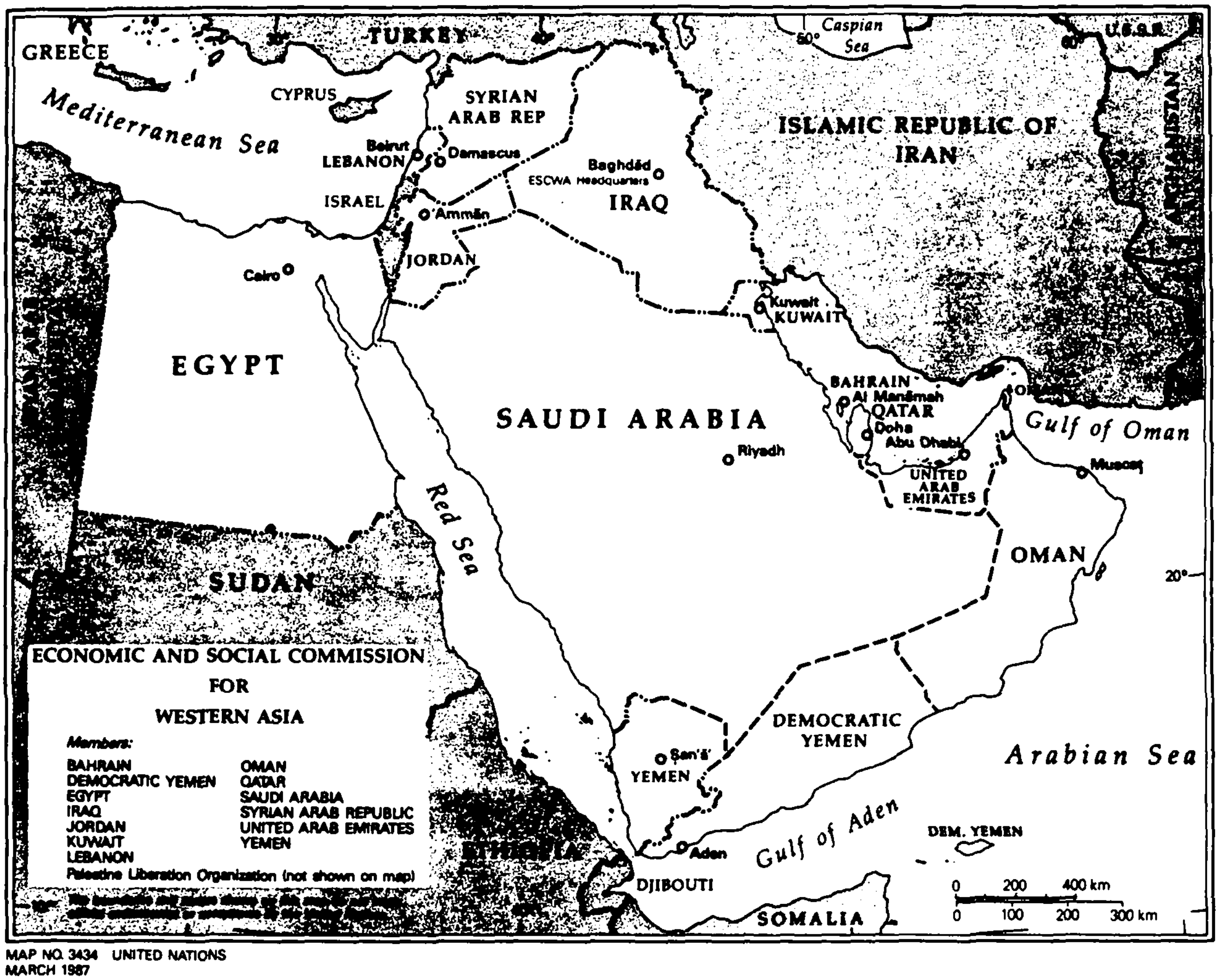
1/ The United Nations Economic and Social Commission for Western Asia (ESCWA) member states are Bahrain, Egypt, Iraq, Jordan, Kuwait, Lebanon, Oman, the People's Democratic Republic of Yemen, Qatar, Saudi Arabia, the United Arab Emirates and the Yemen Arab Republic.




Map 1. Member states of the Economic and Social Commission for Western Asia (ESCWA)

Objectives of the ESCWA study on waste-water reuse are: to evaluate present practices related to augmentation of current water supplied, particularly in the region through utilization of treated waste-water effluents from municipal, agricultural and industrial sources; to outline the minimum acceptable standards and the required treatment to reach those standards for agricultural and industrial application of the treated effluents; and to indicate the required precautions and safeguards against misuse.

This paper summarizes the findings of the ESCWA study. Technical details and specific water quality requirement tables are not included in order to avoid a lengthy presentation.

## 2. Waste water for reuse

### (a) Sources of waste water

The three main sources of waste water are municipalities, industry, and agriculture. The total amount of sewage effluent available would be dependent upon various factors, among which are the number of persons, per capita consumption rates, storm drainage flows (if connected) and inflows from other sources. Industrial waste water quantity and quality are dependent on the type of industry, processes and efficiency rates. In some cities industrial effluents are discharged into the main sewage system, and should be considered together with the municipal sewage. Drainage water reclamation is based on the availability of tail-waters from irrigation systems upstream and/or drainage of rainfall.

In order to have municipal sewage in adequate amounts for treatment for reuse, there must first be a central water supply system; otherwise water consumption and consequently sewage flows would be so small that sewers could not operate. Secondly, there must be a sewage collection network so that the effluent can be collected and transported for treatment. Therefore, for economical operation waste water for reuse is available largely from urban centres.

Most industrial waste waters are derived from washing, flushing, cooling, extractng chemicals, impregnating and other similar operations. Their quantity and nature vary as the products and processes of the plants from which they were produced. Cooling waters consist of large volumes of water discharged at high temperature without any significant contaminant. The effluents from some industries may be highly contaminated, however, which may destroy the biological activity in municipal sewage treatment works, heavily loading those plants and impairing their operation.

Major sources of agricultural waste waters are drainage waters from irrigation projects. The advanced methods of irrigation systems: drip, bubbler, etc. do not produce appreciable amounts of return flows due to their high water application efficiency rates. With surface-type irrigation, however, the return flow volumes may be as high as 35 per cent of the original water applied, depending on various factors. The return flows are usually collected by an appropriate drainage system and allowed to return to streams where they may undergo some degree of natural purification.

(b) Use of treated waste water

Municipal sewage effluent can be used after treatment in various municipal uses such as: street cleaning; fire-fighting; watering of roadsides and divides; watering of municipal gardens, parks and golf courses; streamflow augmentation and other general uses, i.e., ground-water recharge; prevention of salt-water intrusion into aquifers; and recreational impoundments.

In Kuwait the use of treated municipal waste water is limited to the irrigation of forests, fodder crops and certain horticultural products, but in Qatar and Abu Dhabi it is also used for watering of roadsides and divides. There are plans for other uses in the ESCWA region.

Treated municipal effluent is often suitable for various industrial uses, such as cooling, ore separation and other purposes that do not have severe water quality requirements. In the ESCWA region, the petroleum refining industry could be one of the major users of treated waste waters, particularly in the dry Arabian Gulf area, considering the industry's large water requirements. Industrial waste waters can also be treated for recycling in industry, and when industries recycle their own waste waters, the microbiological hazards and environmental pollution rates are largely diminished. Industrial waste-water reuse should be limited to industry only.

Agricultural uses of treated municipal waste waters include: agricultural irrigation and watering of gardens, open spaces, trees, forests and grasslands; fish ponds; and watershed development. Agricultural waste waters, mainly drainage waters, are either directly reclaimed for further irrigation or withdrawn downstream for agricultural, industrial, municipal or other uses. In the ESCWA region this is in practice in Egypt, Iraq, Jordan and Lebanon where such streams and rivers exist.

(c) Treatment required for waste-water reuse

The most important aspect of waste-water reuse is related to the treatment required by, and provided for, the effluent, according to the established water quality criteria for the final prodfuct. Treatment processes suggested by the World Health Organization to meet the given health criteria in waste-water reuse are presented in table 32. The major constituents of waste water that need to be considered in the selection of treatment processes for a reuse scheme are:

(i) Biological: pathogenic bacteria and viruses; parasite eggs; worms and helminths,

(ii) Chemical: nitrates and phosphates; salts, toxic chemicals (including heavy metals).

The contaminats in the waste water must be removed by various methods in order to purify the effluent and make it suitable for various uses. Decisions as to which treatment processes to adopt should be reached after considering various factors, including:

(i) Need to reuse and conserve renovated water;

(ii) Quality requirements of particular uses and users;
(iii) Requirements for the protection of public health and the environment;
(iv) Disposal or use of sludges as a fertilizer or soil conditioner;
(v) Capital cost;
(vi) Operating costs;
(vii) Local facilities and skills for maintenance of mechanical and electrical plants;
(viii) Desirability of providing employment for unskilled labour;
(ix) Availability or possibility of obtaining spare parts;
(x) Source and reliability of electrical power;
(xi) Need to conserve energy resources;
(xii) Size of the required treatment plant;
(xiii) Area of land available;
(xiv) Topography of land available;
(xv) Climatic conditions.

The need to reuse and conserve water has been recognized in the ESCWA region, in particular in the Arabian Gulf area where waste-water reuse has been in practice for a considerable period of time. The quality requirements have been established, generally, as 10 mg/l Biochemical Oxygen Demand (BOD), and 10 mg/l Total Suspended Solids (TSS) mainly for conservation of public health and environment. In Al Ain (United Arab Emirates) the treated sludge is made into a compost for production of humus; in Dubai (United Arab Emirates) there are plans for a sludge treatment plant which will produce fertilizer for marketing.

The capital costs and operating costs in the region are presented in a later section of the paper. A considerable proportion of the professional and skilled manpower to operate and maintain the treatment system is made up of expatriates; however, the governments are making efforts to train an adequate number of nationals.

The oil-rich countries of the ESCWA region do not face any energy problems and obtaining spares is not difficult. The land area required for treatment plants is readily available, and the treatment methods selected for the plants reflect the requirements of the climatic and topographic conditions of the locality. Generally, the activated sludge process followed by sedimentation is preferred for secondary treatment and rapid gravity filters followed by chlorination or ozonation for tertiary treatment. The flatness of land requires pumping in both collection and distribution systems.

Table 32. Treatment processes suggested by WHO to meet the given health criteria in waste-water reuse

| | Irrigation | | | Recreation | | Industrial reuse | Municipal reuse | |
|---|---|---|---|---|---|---|---|---|
| Health criteria (see below for explanation of symbols) | Crops not for direct human consumption | Crops eaten cooked; fish culture | Crops eaten raw | No contact | Contact | | Non-Potable | Potable |
| | A + F | B + F or D + F | D + F | B | D + G | C or D | C | E |
| Primary treatment | +++ | +++ | +++ | +++ | +++ | +++ | +++ | +++ |
| Secondary treatment | | +++ | +++ | +++ | +++ | +++ | +++ | +++ |
| Tertiary treatment | | | | | | | | |
| - Sand filtration or equivalent polishing methods | | + | + | | +++ | + | +++ | ++ |
| - Nitrification | | | | | | | | +++ |
| - Dentrification | | | | | | + | | |
| | | | | | | | | ++ |
| - Chemical clarification | | | | | | + | | ++ |
| - Carbon adsorption | | | | | | | | ++ |
| - Ion exchange or other means of removing ions | | | | | | + | | ++ |
| Disinfection | | + | +++ | + | +++ | + | +++ | * +++ |

Source: Adapted from World Health Organization, "Disposal of Community Wastewater," Technical Series No. 541, 1974, p. 33.

Notes:

Health criteria:

A- Free from gross solids; significant removal of parasite eggs.
B- As A, plus significant removal of bacteria.
C- As A, plus more effective removal of bacteria, plus some removal of viruses.
D- Not more than 100 coliform organisms per 100 ml in 80% of samples.
E- No faecal coliform organisms in 100 ml, plus no virus particles in 1000 ml, plus no toxic effects on man, and other drinking-water criteria.
F- No chemicals that lead to undesirable residues in crops or fish.
G- No chemicals that lead to irritation of mucous membranes and skin.

In order to meet the given health criteria, processes marked +++ will be essential. In addition, one or more processes marked ++ will also be essential, and further processes marked + may sometimes be required.

*Free chlorine after 1 hour.

Waste water must usually undergo primary and secondary treatment, then tertiary treatment is applied as required for reuse.

Conventional treatment of waste water and sewage consists of:

(i) Primary treatment stages: removal of large substances and retention in settling basins to separate liquids from solids by sedimentation;

(ii) Secondary treatment stage: removal of up to 90 per cent of organic matter by biological oxidation.

In general practice, after the secondary treatment and subsequent chlorination, the treated effluent is returned to streams or lakes or used on land. However, when there is a need for reuse of the waste water without any potential hazards for public health, then an additional stage of treatment is required.

(iii) Tertiary (advanced) treatment stage: provides additional decontamination of waste water for municipal, industrial, agricultural and other uses. The tertiary treatment processes are aimed at removing contaminants that may still remain in the treated effluent after the secondary stage. The tertiary treatment processes are directed towards the removal of: odours and off-colours; turbidity/suspended and colloidal solids; organic and inorganic pollutants; plant nutrients (nitrogen compounds and phosphates); trace elements; and pathogenic organisms (parasites, bacteria and viruses).

The treatment sequence may be determined according to the particular requirements of the users and the system. Processes are available for removing ammonia, nitrates and phosphates and for reduction of residual, potentially toxic compounds and dissolved organic substances to very low levels. Dissolved minerals can also be reduced to acceptable levels by ion exchange, electrodialysis or reverse osmosis processes. Disinfection can be accomplished by the use of chlorination, ozonation and ultraviolet rays or by a combination of these.

Parasite eggs, worms and helminths can be largely removed in the primary and secondary treatment stages and the pathogenic bacteria can be killed by chlorine disinfection, but the remaining hazards from viruses after advanced waste treatment are not well known.

### 3. Waste-water reuse application in the ESCWA region

Most of the member countries in the ESCWA region, in particular those located in the arid regions, have very limited natural water resources. Growth of population, rising standards of living and increasing demands by the rapidly developing economies have prompted the governments, especially in the Gulf area, to turn to reuse of treated waste water for a number of purposes, thus freeing the fresh water supplies for drinking and for other uses requiring high quality standards. It has been demonstrated time and again that treated effluent is much cheaper than desalinated water, though lower in quality, but still it can be used for a number of purposes.

The reuse of treated waste water will, in principle, cause an increase in the domestic supplies by substituting for fresh water in agricultural uses. In recognition of the value of this non-conventional water resurce, some member states in the region started utilizing it quite some time ago.

The main projects described in the following pages indicate the extent to which ESCWA member countries are considering using treated waste waters as a new source of supply. Table 33 presents the characteristics of major operating and planned municipal sewage treatment plants in the region which are mentioned in the text.

(a) Waste-water reclamation experience in Saudi Arabia

Saudi Arabia is one of the driest areas of the world, with very little rain and practically no surface water resources. In order to cope with its historical shortage of water, the government has taken steps to develop new sources of water supply as well as to recycle part of the waste water in some areas. Three projects are of particular interest, namely those in Jeddah, Mecca and Jubail. The new industrial city of Jubail was planned from zero to full development whereas Jeddah and Mecca have been traditional centres since ancient times.

(i) The Jeddah project

The city of Jeddah, located on the Red Sea, has historically been short of water. Until about 30 years ago camel trains brought potable water there. This supply was augmented by a small sea-water distillation plant. Additional water was obtained by installation of a pipeline to bring in surface water from wadis in the region and later by increasing the number of desalination plants. Thus the water shortage has been greatly relieved. In Jeddah the water supply had to be continually expanded to meet the demands of a growing population. In the late 1970s when the population was about 1.2 million, the average per capita use was only slightly more than 100 litres per day, but was expected to reach eventually 400-500 litres per day. It was estimated that by the year 2000 the population would reach 2.25 million, consuming 1 million cubic metres of water per day.

In order to cope with the projected future demands, it was planned to construct a number of waste-water treatment plants, each with a capacity to treat 50,000 $m^3/d$ inflow with possible expansion facilities to handle up to 100,000 $m^3/d$. Standards were established based on the guidelines laid down by the convention of Moslem leaders who met in 1979. Accordingly, in order to meet the requirements for "clear, odourless, colourless and tasteless water", the drinking water criteria of the World Health Organization (WHO) were used as the basis of the process design. Although the product water will be regarded as a non-potable supply, this is the first project in the Middle East in which sewage is planned to be treated to meet such high standards.

Table 33. Characteristics of major operational and planned municipal sewage treatment plants in the ESCWA region

| Location | Capacity ($m^3$/day) | Primary and secondary treatment | Tertiary treatment and disinfection | Effluent quality BOD (mg/l) | Effluent quality SS* (mg/l) | Status |
|---|---|---|---|---|---|---|
| Bahrain | | | | | | |
| Tubli (present plant) | 65,000 | Mechanical; extended aeration activated sludge system | Dual media filters, chlorination | 10 | 10 | Operating |
| Iraq | | | | | | |
| Rustomiyah (Baghdad) | 90,000 | Mechanical, sedimentation activated sludge, settling, chlorination | Not applied | 40 + | 60 + | Operating |
| Kuwait | | | | | | |
| Four plants | 380,000 (total) | Sedimentation activated sludge | Rapid gravity sand filters, chlorination | 10 | 10 | Under construction |
| Qatar | | | | | | |
| Al Naijah | 44,000 | Sedimentation, activated sludge | Rapid gravity sand filters, chlorination | 10 | 10 | Under construction |
| Saudi Arabia | | | | | | |
| Jubail | 115,000 | Sedimentation, secondary (not finalized) | Not finalized | 15 | 15 | Planned |
| Jeddah | 50,000 (each unit) | Coagulation, lime softening, sedimentation, recarbonation | Dual media filters, reverse osmosis, chlorination | 1.5 | 0 | Designed |
| Mecca | 50,000 (each unit) | Coagulation, lime softening, sedimentation, ozonation, recarbonation | Dual media filters, chlorination | 1 | 7 | Designed |
| U.A.E. | | | | | | |
| Abu Dhabi | 200,000 (eventual) | Sedimentation, activated sludge | Rapid gravity sand filters, chlorination and ozonation | varies | | Operating |
| Dubai | 130,000 to 200,000 | Mechanical; settlement activated sludge; aeration | Rapid gravity sand filters; chlorination and ozonation | 10 | 10 | Design complete |
| Al Ain | 30,000 to 50,000 | Mechanical; extended aeration | Rapid gravity sand filters; chlorination | 10 | 10 | Operating |
| Other governorates | 120,000 | Mechanical and activated sludge | Not applicable | 40 | 40 | Under construction |

Sources: J.E. Singley, "Wastewater reclamation at Jeddah and Mecca, Saudi Arabia", Proceedings of the Water Reuse Symposium II, Washington, D.C., 1981; Arab Water World, May-June 1984.

*SS= Suspended Solids

Data for a 12-month period indicate that the Jeddah plant effluent has a very high total dissolved solids value (TDS) of 6,065 mg/l, very high conductivity (5,420 micromhos), and very high hardness (1,726 mg/l). The BOD level is about 40 mg/l. To bring the waste water up to the standards specified by the World Health Organization (WHO), the process has been planned to provide complete tertiary treatment. This includes reverse osmosis units which will provide for desalination to reduce the salt content (TDS) from over 5,000 mg/l to less than 600 mg/l. The units are expected to produce 60 per cent product water and 40 per cent reject.

Each plant will provide 50,000 $m^3/d$ of high quality water suitable for municipal, industrial, agricultural and a number of domestic purposes, thus relieving the demand on the city's potable water supply. There is to be an elevated reservoir to hold 50,000 $m^3$.

A preliminary estimate of the total cost of the treatment plant and reservoir was 150 million Saudi Riyals (SRI).[2]

(ii) Mecca project

The city of Mecca has also suffered from a traditional lack of potable drinking water due to the absence of readily available surface and ground-water resources. Much of the present water comes via pipelines from outlying basins. Although there are plans to augment the present supplies, the shortages of water for non-potable uses are expected to continue. Therefore, the study for the Jeddah waste-water reclamation project incorporated a parallel study for Mecca.

Each unit plant is planned to have the same capacity as for Jeddah (i.e. 50,000 $m^3/d$), with the same main treatment elements. The Mecca waste-water data indicate a better quality effluent with TDS = 1,739 mg/l, conductivity of 510 micromhos, and a total hardness of 582 mg/l. The BOD level is 24 mg/l. The process system designed for Mecca is simpler than Jeddah's and the reverse osmosis desalination plant has been totally eliminated since it is not necessary to provide for demineralization. This plant will produce a water with TDS approximately equal to that of the effluent but will still be low enough to be used in non-potable applications. The over-all capital costs are estimated to be SRI 83 million.

(iii) Jubail industrial city

In the new industrial city of Jubail there are extensive plans for a green landscaped city where demand for non-potable water will be quite high if the planning targets are reached. Plans indicate that all domestic effluent would be treated to be used in amenity irrigation and for municipal purposes. In order to avoid use of potable water, industrial waste water may also be treated for use in irrigation by employing advanced treatment methods.

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[2] \$US 1.00 = 3.62 SRI (1985 period average, International Monetary Fund, International Financial Statistics, 1986 Yearbook).

At present, there is no population at the proposed city site, which is planned to have 400,000 people by 1992. Work is continuing on this project (John Taylor & Sons).

(b) Waste-water reclamation experience in Kuwait

The use of effluents in agricultural and forestry schemes has been in practice in Kuwait for many years. Substantial amounts of septic tank contents were collected by tankers and used on government-controlled enclosed reafforested areas where there is no public access. Although Kuwait has been able to develop slightly brackish water sources for irrigation of landscaped areas and private and public gardens, effluent is being increasingly used on restricted areas since the cost of brackish water and desalinated potable water is four to six times as much as tertiary treated effluent. In 1977, an irrigation scheme with a projected total area of 920 hectares was put into operation, utilizing the 24,000 $m^3/d$ available to the project. This water was used for irrigating alfalfa, winter forage crops, barley, and a small amount of different vegetables.

The Agricultural Development Programme of the Government of Kuwait started experimental studies on the use of clarified sewage effluent for irrigated agriculture in the 1960s, and the Food and Agriculture Organization of the United Nations (FAO) provided the State of Kuwait with assistance (United Nations FAO, 1978).

At present, over 7 million $m^3$ of effluent a year are utilized from the Ardiyah treatment works and it is planned ultimately to make use of 125 million $m^3$ of treated sewage each year. This large reuse scheme in the Middle East will provide treated water with a much lower dissolved solids content than ground water, thus making it suitable for a wide range of plants.

The planning horizon for the Kuwait effluent utilization project extends to the year 2010, for an estimated population of 700,000 people. The project, which is under construction at present, will treat 380,000 $m^3/d$ of treated waste water in three mainland and one island treatment plants. The civil engineering work on tertiary treatment elements for the effluent from the main three mainland plants was completed in 1981. The design salinity level is about 2,000 micromhos. For irrigation of fodder crops and forestry the effluent standards are to be a coliform count which is below 1,000/100 ml and for other crops below 100/100 ml (Banks, 1980).

The distribution works includes bulk transmission by pipeline, storage and distribution. The design average and peak daily volumes of treated effluent are to be 0.4 and 0.68 million $m^3$, respectively, by the year 2010. The project includes four reinforced concrete reservoirs each with a capacity of 170,000 cubic metres, some smaller reservoirs, and eight pumping stations (John Taylor & Sons).

It is planned that, following three days of treated effluent storage and pumped conveyance, applications will mainly be via side roll sprinklers for fodder crops, drip emitters for forestry, and trickle strips for vegetables.

The present policy in Kuwait restricts the utilization of treated effluent to the irrigation of forests, fodder crops and certain horticultural products, and therefore, uses for irrigating public parks, either for municipal purposes or for private garden watering and toilet flushing, are not included in the plan for the future. It is expected that there will be controlled distribution for forestry and agriculture and for cooked vegetables (Cowan and Beynon, 1981).

It is planned to develop 2,500 hectares for agriculture and 9,328 hectares for forestry by the year 2010, in various areas in Kuwait.

(c) Waste-water reclamation experience in Qatar

Qatar has a long history of effluent reuse; some municipal areas of Doha have been irrigating with treated effluent since the 1950s. Water demand in the domestic and commercial sectors of the country has increased sharply from 4 million $m^3$/year in 1964 to 48 million $m^3$ in 1980. Growth has been particularly rapid since 1975, consumption having risen by a factor of over 3. There are no permanent surface water courses in Qatar, and the water supply has traditionally been by ground-water extraction. However, because of the rapid depletion of the northern aquifer, extraction from these well fields was stopped in 1978, and the water supplies to Greater Doha for domestic, industrial and commercial purposes have almost completely been met by desalinated water (Balfour-Halcrow, 1981). Under these circumstances, water available for agricultural purposes has been very limited, and reuse of waste water has gained increasing acceptance over the years.

In earlier years, the treated sewage was pumped to a number of elevated water storage tanks from which it was collected by road tankers and was used to irrigate municipal gardens and other areas in the city, and later pipelines were laid in order to avoid traffic delays. There is an extensive trunk sewage system installed in the city of Doha. However, after a rapid increase in sewage flows, connection of houses and properties to this system was restricted due to the deficiencies in the capacity of the sewage treatment works located to the south of the city at Al-Naijah. At the treatment works, sewage receives primary sedimentation and a portion gets biological treatment by trickling filters, but the works are overloaded, and as a result the effluent is of poor quality. Of the flow receiving biological treatment, about 2,000 $m^3$/d is chlorinated and returned to Doha for municipal irrigation. In some parts of the city a distribution system for treated sewage effluent exists. The rest of the effluent, thought to be in excess of 30,000 $m^3$/d, is discharged to a remote area of desert where it has created a heavily vegetated lake.

Construction of the expansion of the sewage treatment facilities at Al-Naijah has already started; these facilities will be serving a population of 180,000 when completed. The total capacity will be 44,000 $m^3$/d. In addition, there are plans to construct a second treatment plant to the north of the city. All the treated effluent is to be used in agriculture, horticulture, and public amenities, since the discharge of even tertiary effluent into the sea is understood to be unacceptable.

At present, the salinity level of the effluent is approximately 2,000 mg/l and is expected to decrease when it undergoes tertiary treatment when the new works are completed, which can make the treated effluent suitable for agricultural use (Balfour-Halcrow, 1981). Similarly, the total dissolved solids content of the sewage was estimated to be around 2800 mg/l. Boron, which is toxic to many crops, has been detected in the sewage at levels of 1.5-3.0 mg/l, depending on detergent usage and water consumption (John Taylor & Sons).

By international standards, the treated sewage effluent would be suitable for irrigation of fodder crops or crops used for human consumption after cooking. Therefore, it has been recommended that the use of the treated waste water be restricted to irrigation of crops in these two categories.

Furthermore, there are plans to extend the present use of the treated waste water for municipal landscaping. The municipal demand was estimated as 800,000 $m^3$ in 1980 and it was calculated that this figure would rise to 11 million $m^3$ by the year 2000 (Balfour-Halcrow, 1981).

As mentioned earlier, the bulk of the treated sewage effluent will be employed in agriculture. Part of it will be pumped by a pipeline over 40 km in length to an area where it is proposed to gradually develop a total of 1,000 hectares by the year 2000 under various crops. Although the internal rate of return of such a project was estimated to be relatively low, it has been recommended, considering the non-monetary benefits which would arise from such a project in the areas of food security, the provision of feed for expansion of Qatar's livestock industry, and as a model for agricultural development. It has also been recommended that irrigation application should be by self-propelled sprinkler jet-guns (UN/FAO, 1980).

The remaining part of the treated waste water will be pumped back to Doha and used for irrigating trees and in landscaping.

(d) Waste-water reclamation experience in the United Arab Emirates

The United Arab Emirates (UAE) located on the south-western shores of the Gulf, have very limited surface water resources, with some intermittent streams in the mountains in the southern part of the country near Oman. The average annual rainfall of the Emirates does not exceed 75 millimetres (mm) and the country has resorted to non-conventional sources of water in order to augment its inadequate supplies. In some parts of the country the use of treated sewage effluent for watering of public parks and for landscaping has been in practice for a number of years.

(i) Use of treated waste water in Abu Dhabi

Abu Dhabi has a very extensive scheme of using treated sewage effluent in irrigating the municipal areas. Parklands and playgrounds are irrigated with potable water. The use of treated sewage effluent for irrigating amenities started in 1976, and the system was designed to accommodate treated effluent from a population of 665,000, and to eventually provide 70 million $m^3$ of effluent a year. For public health reasons, this use has been restricted to areas where the public has limited access, i.e. in central divides in highways (John Taylor & Sons). The designed salinity level is 6,000 micromhos, since the sewage available for treatment was initially considerably more saline than the potable water obtained from the desalination plant and from the fresh-water wells which constitute the industrial water supply of the city (Banks, 1980). After taking some restrictive measures, the average conductivity of the effluent fell to around 1,400 micromhos, with a range of 1,200-2,500 micromhos, thus, increasing the types of plants which could be grown by using treated waste water. However, this increased the public health risks, since the effluent was no longer unpleasant to drink or to use for other domestc purposes.

Therefore, the treated waste water distribution system is clearly marked to differentiate it from the potable water, in order to avoid any possible confusion. Furthermore, the municipal areas readily accessible to the public are not watered by treated effluent, and where applied, the treated sewage irrigation systems operate under low pressure to avoid blowing any of the spray from the irrigation system into the populated areas by wind.

(ii) Use of treated sewage effluent in Al Ain

Al-Ain is within the limits of the Government of Abu Dhabi in the UAE. The population of Al Ain was only 50,000 in 1975, but has grown more rapidly than envisaged, reaching 140,000 in 1982, and it is forecast to increase to 250,000 persons by the year 2000.

The city is divided into a number of waste-water collection basins, each draining into a pumping station whch raises the sewage either into the gravity trunk sewer or to a main sewage pumping station for conveyance to the treatment works.

The treatment works were designed to make possible the use of treated sewage effluent for selected irrigation purposes in the city. Irrigation of crops that are likely to be eaten raw or partially cooked is not allowed.

Aerobic digestion is employed in the treatment of the surplus activated sludge, followed by drying on open beds. Sludge cake is then taken into a nearby composting plant for production of compost to provide humus for plants at roadsides and at other permitted locations (Deane and others, 1983).

(iii) Use of treated sewage effluent in Dubai

The existing sewage treatment plant in Dubai is not adequately equipped for appropriately treating sewage effluent for reuse, and the product, which is of rather poor quality, is used in the watering of some parks by means of water hoses. There are efforts for equipping this plant to produce effluent with BOD and suspended solids levels of 20 mg/l. However, this is only a temporary measure since there are plans for setting up a completely new sewage treatment plant.

The design work on the new plant was complete and a contractor was selected in mid-1984. According to the design, the treatment works are planned to produce 130,000 $m^3/d$ by 1984 and 200,000 $m^3/d$ by 2005 (GWE Consulting Engineers, 1982). The treatment plant will also process surplus sludge by digestion, conditioning and thermal drying so that it will be suitable for use without restriction, by agricultural and market garden users.

(e) Waste-water reclamation experience in Egypt

Cairo, the capital city of Egypt, is the largest city in Africa and one of the fastest growing. The population, less than 2 million in 1950, reached almost 8 million by 1980 and is predicted to grow to 15 million by the end of this century. This rapid increase in population has caused problems, during a period of economic stringency. It has been reported that sewers in many parts of the city are grossly overloaded and that they cannot be efficiently maintained. Flooding of the streets with sewage occurs regularly. A large amount of the 1.5 million $m^3$ of the city's daily sewage receives little or no treatment and passes along open drains through populated areas (John Taylor & Sons).

A report prepared in 1977 on Cairo waste water recommended the use of treated effluent for desert reclamation schemes outside the city by using treated sewage effluent for agricultural development. Proposals included sprinkler and drip irrigation systems for growing citrus fruit, cereals and vegetables. There were also studies into the use of the nutrients in the sewage for fish farming, based on the likely levels of nutrients in the effluent (John Taylor & Sons, 1977). This use of sewage has been in practice for centuries in the Far East, and considering the unmet demand for protein, this could very well make it a complementary and economic alternative. These projects have not yet materialized, however, and research work on treated sewage application in agriculture is continuing.

(i) The Greater Cairo waste-water project

The Government of Egypt commissioned a master plan and feasibility study in 1977, to be followed by a design phase, which is currently under way. The whole project comprises about 40 km of rock tunneling for main and subsidiary sewers, related lift stations, conveyance culverts, force mains and four sewage treatment works.

The treated sewage effluent will be employed in agriculture and aquaculture, and it is envisaged to develop initially up to 40,000 acres of land under irrigation. The system cannot be connected to the Nile irrigation system due to a law passed in 1972 banning any discharge to that system.

(ii) Reuse of drainage water for irrigation purposes

The use of drainage water has long been in practice in Egypt. Records indicate that the quantity of drainage water used for irrigation in both the Delta and Upper Egypt has been over 5 billion $m^3$. In the Delta the total average annual available drainage water has been estimated to be between 14 and 16 billion $m^3$. The amount of drainage water discharging to the Nile in Upper Egypt is about 2.3 billion $m^3$ per year, and this amount is on the increase due to extension of the public drainage systems (El-Gendi and El-Ghamry, 1977).

Reuse of drainage water is practiced by means of direct pumping from the drains to the feeder canals, delivery of the total discharge of the drainage pumping stations into the canals, and by indirect reuse of the drainage water by discharging the drainage water to the main course of the Nile or its branches to be used downstream.

It has been determined that the drainage waters in Egypt generally have a low sodium hazard potential throughtout the year and a mostly medium to high salinity hazard, which make them safe for use on the heavy textured soil which is predominant in the Nile Valley and Delta. However, the Ministry of Agriculture has been studying the possibility of using drainage water on soils of different characteristics under various irrigation and leaching practices, crops and agronomic techniques. The Ministry of Irrigation has been conducting a large programme for field monitoring of the quantity and quality of drainage water on a large network of drainage canals and the branches of the Nile (see part three, chapter IV of this volume).

There is an ongoing research project at the National Research Centre on the treatment requirements of urban sewage for reuse in agriculture.

(f) Water reuse activities in Bahrain

The Tubli water reuse project, currently in the design phase, will supply up to 50 per cent of the water required for irrigation in Bahrain when it is completed by the year 1990. At present, the Tubli treatment plant treats a daily average of 65,000 $m^3$/d of sewage flowing into Tubli Bay. Soon the first treated water from Tubli, nearly 3,500 $m^3$/d will be used to irrigate roadside verges and small parks (Arab Water World, May-June 1984).

The project involves the construction of pipes and pumping stations to take water to the new agricultural area to the west of Isa Town. The waste water will be treated up to the tertiary stage and will irrigate at least 500 hectares. This is between a third and a half of the agricultural area on Bahrain's main island. The project will not only dramatically cut down on the amount of ground water extracted but will actually replenish the aquifer through the percolation that occurs during irrigation.

There are also plans to increase the treatment capacity of the Tubli plant to an average of 163,000 $m^3$/d during the period 1990-2000.

(g) Water reuse activities in Jordan

In the water resources master plan for Amman, it is planned that 10 million $m^3$/year will be pumped from the King Talal Dam to contribute towards meeting the total water supply demand of Amman which is nearly 50 million $m^3$ per year. The effluent from Amman, after being treated at a treatment plant and flowing underground, will emerge along the Zarqa River course and will return to the reservoir of the King Talal Dam where the natural purification process is expected to continue. The water mixed in the reservoir will then be pumped to Amman to be purified to the required degree at a treatment plant for use again.

(h) Other water reuse activities in the ESCWA region

There are plans to construct a sewage treatment plant with a capacity to serve a population equivalent of 150,000 to the capital city of Sana'a (Yemen Arab Republic). The treated sewage effluent is planned to be fit for irrigation or aquifer recharge purposes.

In Iraq, treated effluent directed to the Tigris River from treatment plants along this river and the Diyala River goes through additional purification through natural processes in the river before it is withdrawn for irrigation downstream.

It appears that waste-water reuse has been considered for the city of Damascus. The city would utilize treated municipal sewage for irrigation purposes. However no plan of action has so far been developed.

## 4. Economics of waste-water reuse

Water reuse in a community depends primarily upon economic factors. Although the technology for waste-water reclamation is available, economic considerations limit its use to special locations or particular purposes. As demands for existing resources in water-scarce areas become greater, water reuse gains more potential in certain uses and if used, releases natural sources of water for potable supplies. Pollution control measures are becoming stricter all over the world and such regulations are also being introduced by the ESCWA member countries. An increasing number of sewage treatment plants are being established where the effluent is treated to levels that will not cause pollution and will allow some direct use, or after additional treatment, almost any use.

In the detailed economic analysis of a water reuse project, it might be necessary to relate the short, mid- and long-term price of water conservation and reuse strategies to the cost of supply, interest rates, operation and maintenance costs, etc. to derive the appropriate cost of the various strategies. These costs are compared with normal no-strategy costs as well as with the costs of alternative water production schemes. Benefits are likewise quantified and compared. The analysis is handled on a case-by-case and regional basis, in terms of the current value of the future benefits and costs in addition to the current costs. In order to perform a reliable analysis, required data include information on: appropriate costs; benefits; discount and inflation rates; and such technical information as performance characteristics, energy requirements, reliability and project length. However, the economic analysis of water reuse projects is not always used as the only criterion for project appraisal and implementation. In many arid lands, such as in the Gulf countries, there is a national desire to develop and maintain public green areas for amenity purposes. This type of utilization is often adopted as the sole use with others being excluded. In such a situation where the benefits are not tangible, it is difficult to attempt a complete economic analysis.

It is expected that in the early years of operation, the actual unit cost of water would be higher, since the full design capacity will not be reached until the population rises to design levels and produces the designed volume of effluent for treatment.

(a) Cost of a waste-water reuse scheme

For a large municipality, a sewage treatment plant is a necessity for pollution control, where the effluent is treated through primary and secondary treatment processes. Only the cost of the distribution and tertiary treatment, if this component is incorporated, would be extra for waste-water renovation.

However, in the ESCWA region, it appears that even if the whole project cost is charged to treated waste water, the unit cost is quite reasonable. Table 34 presents the cost estimate breakdown for the new waste water treatment plant for waste-water reuse in Dubai. The total cost of items involving effluent purification processes from inlet works through tertiary treatment is 233.4 million dirhams ($63.95 million)[1] and constitutes 0.27 per cent of the total overall scheme cost. Tertiary treatment cost is only six per cent of the total. The annual operation and maintenance costs of the system were estimated to be 2.75 per cent. For project life periods of 20, 30, 40 and 50 years at amortization rates of 6-12 per cent, incorporating the running cost and considering the system total, the unit cost for treated effluent was estimated to be between $0.35-0.62 per $m^3$.

Similarly, the total cost of the complete tertiary treatment plant in Kuwait, together with the distribution system and appurtenant structure costs was estimated to be 110 million pounds sterling ($225.5 million) in 1980/81 (John Taylor & Sons; Banks, 1980). Assuming the same capital recovery and operation and maintenance costs as above, the unit cost of effluent is estimated to vary between $0.18-0.31 per $m^3$.

(b) Alternatives to waste-water reuse

Water reclamation for increased supplies depends upon the availability, reliability and cost of developing ground and surface sources of water, and upon the cost of alternative non-conventional water supplies. In the ESCWA region desalination of sea water and brackish waters is the main alternative in practice.

Normally, water supplies derived from conventional surface and ground waters are cheaper than the non-conventional supplies. However, in many parts of the world the conventional sources are inadequate to meet the total demand. This is particularly true in the Gulf area of the ESCWA region where sea-water desalination provides a major portion of the water supplies. Table 35 illustrates the increase in the volume of desalinated water produced in Qatar and Kuwait in receitn years, compared with ground-water extraction. In Kuwait distilled water is mixed with the brackish ground water before it is utilized. Table 36 presents the current situation and the planned development of desalination at various localities in the United Arab Emirates.

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[1] $US 1.00 = dirhams (Dh) 3.65 (1981 period average).

Table 34. Cost breakdown for the 200,000 $m^3$/d waste-water treatment plant planned for Dubai Municipality

| Components of the scheme | Component cost (1981 prices) Dirhams (million) | Dollars (million) |
|---|---|---|
| Power supply | 6.7 | 1.84 |
| Access road | 1.5 | 0.41 |
| Drinking water supply | 1.3 | 0.36 |
| Telephone | 0.5 | 0.14 |
| Influent pipeline | 215.0 | 58.90 |
| Effluent pipeline | 170.0 | 46.58 |
| Pumping stations | 40.0 | 10.96 |
| Inlet works | 16.9 | 4.63 |
| Primary settlement | 22.5 | 6.16 |
| First stage biological treatment | 60.1 | 16.47 |
| Second stage biological treatment | 79.2 | 21.70 |
| Coagulation | 4.6 | 1.26 |
| Tertiary treatment | 50.1 | 13.73 |
| Sludge treatment | 45.3 | 12.41 |
| Administration and service buildings | 25.1 | 6.88 |
| Power supply (internal) | 4.3 | 1.18 |
| Pipework | 56.4 | 15.45 |
| Ancillaries | 30.9 | 8.47 |
| Siteworks | 24.6 | 6.74 |
| Total cost (1 $ = 3.65 Dh) | 855.0 | 234.25 |

Source: GWE Consulting Engineers, "New Dubai Sewage Treatment Plant Feasibility Study", Dubai Municipality, May 1982.

Table 35. Fresh water production from ground water and by desalination of sea water in Qatar and Kuwait
(1,000 $m^3$ per year)

| Year | Qatar: Ground water | Qatar: Desalinated sea water | Qatar: Total | Kuwait: Potable ground water | Kuwait: Brackish ground water | Kuwait: Desalinated sea water | Kuwait: Total |
|---|---|---|---|---|---|---|---|
| 1975 | 6,210 | 10,400 | 16,610 | 1,759 | 37,859 | 50,973 | 90,591 |
| 1976 | 6,070 | 10,220 | 16,290 | 1,927 | 41,177 | 63,436 | 106,540 |
| 1977 | 6,000 | 14,800 | 20,800 | 2,227 | 42,400 | 76,505 | 121,132 |
| 1978 | 5,400 | 23,060 | 28,460 | 2,523 | 46,277 | 91,809 | 140,609 |
| 1979 | 4,570 | 31,950 | 36,520 | 264 | 49,650 | 104,664 | 154,578 |
| 1980 | 3,670 | 44,350 | 48,020 | 573 | 51,450 | 106,155 | 158,178 |
| 1981 | 3,000 | 51,000 | 54,000 | 791 | 55,123 | 113,345 | 169,259 |
| 1982 | 3,964 | 53,860 | 57,824 | 545 | 64,632 | 129,623 | 194,800 |

Sources: Ministry of Planning Central Statistical Office, Annual Statistical Abstract, Kuwait, 1983.

Central Statistical Organization, Annual Statistical Abstract, Qatar, 1984.

Table 36. Projections of fresh water production from ground water and by desalination at various locations in the United Arab Emirates
($1,000\ m^3$ per year)

| Locality | 1981 Ground water | 1981 Desalinated water | 1981 Total | 1988 Projected total | 1998 Projected total |
|---|---|---|---|---|---|
| Abu Dhabi and Al-Ain | 105.9 | 197.1 | 303.0 | 2,493.0 | 4,683.0 |
| Ruwais | - | 116.8 | 116.8 | 408.8 | 525.6 |
| Dubai and Jabal Ali | 167.9 | 237.3 | 405.2 | 916.2 | 989.2 |
| Sharjah | 219.0 | 146.0 | 365.0 | 511.0 | 584.0 |
| Ajman | 18.3 | - | 18.3 | 146.0 | 146.0 |
| Umm Al-Kuwain | 16.8 | - | 16.8 | 53.3 | 89.8 |
| Ras Al Khaimah-Galilah | 67.2 | 98.6 | 165.8 | 511.0 | 806.7 |
| Central region | 10.2 | - | 10.2 | 55.8 | 55.8 |
| Fujeira and East Coast (Plant Qidfa) | 84.0 | - | 84.0 | 211.7 | 211.7 |

Source: Ministry of Electricity and Water, "Prospects of drinking water supply in the UAE: A National Report," United Arab Emirates, 1980.

Note:
In 1988 and 1998 the ground-water extraction is expected to be kept at 1981 extraction levels.

Since not all of the water produced is used for domestic purposes, it may be possible to meet a large percentage of the total demand by treated waste water. For instance, an 85,000 $m^3/d$ sewage treatment plant in Qatar would produce (on a 340 working day basis) 28.9 million $m^3$ of treated waste water per year, which is half of the total potable water produced in 1982. Similarly, a series of treatment plants with a total capacity of 300,000 $m^3/d$ in Kuwait, would provide 102 million $m^3$ of treated effluent, which is more than half of the total water produced in 1982. A 50 per cent recovery rate is not to be considered high in a municipality with proper water distribution and sewage collection systems. Being quite aware of the potential of waste-water reuse, Qatar, Kuwait and a number of other ESCWA countries located in arid areas, have taken measures towards meeting part of their requirements through waste-water reuse.

The available unit cost estimates for treated waste water in the region, together with desalination costs, are presented in table 37. From this information it can be concluded that in the early 1980s the cost of complete treatment of municipal waste water for reuse was not above \$0.40 per $m^3$ in the ESCWA region. This is a very favourable unit cost compared with that of desalination of sea water, though the latter produces potable water and reclamation for reuse should be considered when the water is not to be used for potable, domestic or close contact purposes. Desalination of brackish waters by reverse osmosis-type membrane processes produce fresh supplies at comparable or cheaper prices than waste-water treatment, but an unlimited supply of brackish water is necessary.

Cost comparisons of production of desalinated water and treated sewage effluent give a fair indication of the potential for waste-water reuse in the ESCWA region, however.

## 5. Policy, planning and management of waste-water reuse

### (a) Policy and planning for waste-water reuse

In order to initiate any development in the waste-water reuse field, policies must be established ahead of other activities. First, the need for reuse should be assessed vis-a-vis the other sources of water available for present and future development in various sectors of the economy. Once waste-water reuse is ascertained as a competitive way of augmenting the water supplies, then the policies and options can be laid out according to the requirements and characteristics of the country. These can be reviewed from time to time to meet ever-changing conditions.

Policy and planning for waste-water reuse should generally include the following aspects:

(i) Identification of the potential sources (populations of town and available amounts of waste water, existing sewage system);

(ii) Identification of the possible uses and users;

(iii) Establishment of the criteria for treatment for various uses;

(iv) Establishment of safety levels and measures to maintain them;

(v) Establishment of the systems for control of water quality and its applications;

Table 37. Comparison of unit costs of treated municipal sewage effluents and desalinated water

| Location | Base Year | Treated effluent Unit cost range (US$/m³) | Desalinated water Unit cost range (US$/m³) | Remarks |
|---|---|---|---|---|
| U.A.E. | 1982 | 0.30 - 0.41 | 1.00 - 1.45 | |
| Qatar | 1981 | 0.24 | 1.14 - 1.16 | Energy supplied at zero cost |
| | 1981 | | 1.45 - 1.64 | Energy supplied at market cost |
| Kuwait | 1981 | 0.18 - 0.31 | 2.50 (1984) | |
| Bahrain | 1984 | 0.28 | | Without a reverse osmosis unit |
| | 1984 | 0.84 | | With a reverse osmosis unit |
| Egypt | 1980 | 0.05 - 2.90 | | Primary treatment cost of industrial waste waters |
| Saudi Arabia | 1980 | | 0.04 | Desalination of brackish waters by reverse osmosis |
| | 1979-82 | | 0.71 - 1.23 | Desalination of sea water by multistage flash system |
| United States (California) | 1980 | 0.13 - 0.32 | 0.87 | |
| South Africa | 1980 | 0.13 - 0.27 | | Various areas |
| - Windhoek | 1980 | 0.31 | | Adjusted to 1980 cost by using 10 per cent inflation rate |

Sources:

Associated Consulting Engineers International, "Report on Treated Effluent Sludge and Compost Utilizaton", State of Bahrain, 1984.

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(vi) Educating the people on the uses and potential hazards;
(vii) Establishment of legislation on water reuse;
(viii) Organization of institutions for development, operation and maintenance of reuse systems, and for undertaking research activities.

In planning for the reclamation of municipal effluent and waste waters from other sources, it is essential to consider the purpose for which the treated water is to be utilized and whether it will be recycled many times.

Large and increasing volumes of water are necessary for industrial and agricultural development and production, especially in arid countries. Water is vitally important in terms of national development and political independence. Beautifying the environment creates another burden on the limited water resources of a country. Thus, in planning the use of treated waste waters, priority must be given to public health and environmental considerations due to the potential hazards to health, related to the chemical, biological and pathogenic constituents of the waste water. Once the economically reclaimable quantities are estimated, the quality criteria are established and the necessary treatment methods and processes to achieve these standards at acceptable costs are identified.

In the ESCWA region, as a major policy item, treated waste water has been restricted to uses minimizing human contact.

(b) Precautions and safeguards in waste-water reuse

The most critical element in waste-water reuse is that of protecting public health. The reclaimed water must be treated and used in such a way that it will not be a danger to human beings and the environment. Pipes carrying treated effluent and drinking water must be clearly differentiated to avoid drinking by municipal workers and any animals. Bodily contact of agricultural workers with the treated effluent and exposure to aerosol drift must be minimized to reduce short-term and long-term effects of any remaining contaminants in the effluent.

In order to protect public health, the effluent would either have to be properly treated before irrigation application, or its use should be restricted only to certain crops so that improperly treated waste water will not come into contact with any part of a plant used for human food or animal feed.

In the ESCWA region, waste-water reuse has been in practice, though on a limited scale, over a number of decades. So far no epidemics or serious infections have been reported due to the limited use of the treated effluent and the safety precautions undertaken.

In Kuwait the policy related to treated waste water restricts its use to the irrigation of forests, fodder crops and certain horticultural products. Future planning for Kuwait does not include the use of treated waste water to irrigate public parks and gardens, or its use for municipal purposes such as fire-fighting and street cleaning, or for domestic purposes such as garden watering and toilet flushing.

However, in Qatar, some municipal areas of Doha have been irrigated with treated waste water for nearly 30 years without any noticeable hazardous effects on the public health or on the environment. There are plans for extending the present municipal use of the treated effluent for landscaping when the bulk of it will be used in agriculture.

Future projects elsewhere in the ESCWA region are planned for limited use of treated effluent but with broader applications in various industries as well as for municipal and agricultural purposes. The standards set to be met by the treated effluent reach those of the drinking water, particularly in Saudi Arabia, and strict application of these requirements and careful practices in the field should minimize any possible hazards to public health and the environment.

Water reuse deserves a high research priority, because it will be a highly competitive alternative among the non-conventional sources of water. Overall, research should centre on ways to reduce cost, to combine secondary and tertiary treatment processes and to answer concerns about virological hazards. However, studies on viruses cannot be undertaken at the laboratories normally attached to treatment plants. This requires specially equipped institutions that may be only a few in number, if any, in a developing country. Under these circumstances, research and studies are generally directed towards development of low-cost treatment techniques, and monitoring of possible effects of purified effluent use with a view to prevent any health hazards. Other research subjects would require the attention of developed countries which possess an adequate number of institutions properly equipped to enable them to undertake these specialized studies.

(c) Legislation for waste-water reuse

In order to ascertain that the policies established for waste-water reuse are followed properly, satisfactory legislative measures and proper management practices need to be introduced. The legislation should be so developed that it fits well into the over-all legislative framework of the country, with adequate provisions for all aspects of activities related to waste-water reuse. Management of effluent treatment as well as its distribution to users should be properly supported by legislative measures since this is a practice which requires particular attention in order not to compromise the safety of the public health and the environment.

Legislation and regulations should also have provisions for all financing, planning, construction and operation aspects of waste-water reuse systems. Minimum design and operational criteria and standards should be established by legislation which should also promote the selection and implementation of the most appropriate and applicable combination of the necessary systems for waste-water reuse.

Legislation should establish water quality standards for various uses and also provide regulations for discharges into the sewage collection systems. It should also cover the priorities and water rights as well as the sale and distribution of treated waste water.

(d) Training for management of waste-water reuse

Thorough training of personnel is essential to make water reuse projects a success by maintaining safe and economic operations. Training would be necessary at different levels. If there are existing sewage treatment plants that will become reuse facilities by the addition of other processes, all the staff may need to undergo training on the additional aspects of their new work.

The training can be organized for executives and managers; middle-grade professionals; and auxiliary personnel. Local and regional institutions and universities may be able to offer training courses for some lower-level professionals, but in the developing countries in the earlier stages of development, treatment plant managers and high-level professionals would probably receive the greatest benefit from overseas training. For auxiliary personnel, local training courses may be sufficient.

## 6. Conclusions and recommendations

Waste-water reuse has been in practice in the ESCWA regon for a considerable period of time; however, it has been limited in application and only recently plans have been formulated for large-scale development of this non-conventional source of water. In part, lack of knowledge of the long-term effects of the use of treated effluent for various purposes, and also the availability of other sources of water have prevented wider application. However, with the development of new technology and the rising cost of water developed with conventional methods or by desalination, a new outlook has come to the field of waste-water reuse.

The sources, uses and treatment methods involving waste waters do not show significant variations from one arid region to another. The principles are the same. Therefore, the recommendations that follow on various aspects of waste-water reuse are applicable to all of the ESCWA member States, as well as water-short areas in other regions. If some recommendations are applicable only to certain countries these are identified as required.

The following are recommendations for waste-water reuse application.

(a) Use of treated effluent for potable and domestic purposes is not recommended. When the waste water is to be used for purposes where human contact is unavoidable, then it should be treated close to the established drinking water standards.

(b) The use of treated waste water is recommended in water-short developing countries for the following purposes provided that the minimum standards required for each particular application are met:

(i) Municipal uses: watering of roadsides and divides, municipal parks, gardens, golf courses etc.; fire-fighting, and street-cleaning.

(ii) Industrial uses: largely for cooling and boiler feed and in some industries as process water and for ore separation. Treated waste-water reuse is not recommended in food industries since a mix-up between the treated waste water and fresh water supply systems may cause a major disaster.

(iii) Agricultural uses: irrigation of forests, fodder crops, and other crops that will not be eaten raw or will not contaminate kitchen utensils. Fishponds and aquaculture may also be considered as possible applications.

(iv) Other uses: streamflow augmentation; ground water recharge, and prevention of salt-water intrusion into aquifers are other possibilities. Use of treated sewage effluent in recreational ponds is not recommended.

(c) In the early 1980s the unit cost of treated municipal effluent in the region was established as $0.40/m$^3$. In planning for augmentation of existing water supplies for non-potable industrial, agricultural and municipal purposes, if the cost of alternative sources is estimated to exceed the above figure, then waste-water reuse should be seriously considered. Reuse will require that a population centre is nearby with over 100,000 people and with an existing waste-water collection system.

(d) A survey of new treatment plants that will reuse municipal waste water has indicated that 10 mg/l BOD and 10 mg/l TSS are established as minimum effluent quality standards in the Gulf countries. These criteria are recommended for application in treatment plants elsewhere. However, special standards required for particular uses must also be met. In planning of use of waste-water for various purposes, the common minimum treatment requirements should be met in the principal treatment plant. This is generally more economical, as special requirements of a certain industry can be met by additional treatment by that industry itself. Local conditions will be the most important factors in deciding on whether to use a centralized plant or a number of individual plants and in the selection of the required process.

(e) If a government takes the decision of using treated waste water as a source of supply, a policy regarding the use of treated effluent must be established. For example, Kuwait's policy is to restrict its use to the irrigation of forests, fodder crops and certain horticultural products. Such a policy must be backed up by adequate regulations and satisfactory institutional arrangements to promote successful implementation, including legislation and training.

(f) It is recommended that the following precautions and safeguards are taken in waste-water reuse, particularly in the ESCWA region:

(i) Wherever treated waste water is used, the established standards and regulations should be strictly followed from the beginning, and if necessary these standards should be revised after long-term monitoring of the activities. Since any breakdown in the treatment plant could cause deterioration in the quality of the treated waste water, continuous and safe operations should be secured, and any end product not meeting the standards should not be released for use.

(ii) The pipes and other system components carrying fresh water supplies and the treated sewage effluent should be clearly differentiated to prevent cross-connections and accidental use of treated effluent for potable purposes.

(iii) Municipal and agricultural workers who have to use treated waste water as part of their work should be well-informed about the particulars of this practice and required to minimize their contact with the treated effluent.

(iv) Industries should be encouraged, or if necessary, pressured to recycle part of their waste waters and treat the rest to acceptable standards so as to minimize pollution. Under certain circumstances industrial waste waters should not be mixed with municipal sewage. This would be in situations where they have characteristics that would make the job of treatment of the combined wastes very costly. Waste-water reuse by various industries has a great potential in the ESCWA region.

(v) Return flows as drainage water to streams should be strictly monitored since the length of the natural purification process may not be adequate before downstream use, causing accumulation of salts and undesirable substances. If necessary the drainage waters should be given adequate treatment before or following their return to streams. Purification of industrial wastes by natural processes in streams is not recommended.

(vi) In streamflow augmentation the treated effluent must meet established criteria so as not to endanger the health of human and animal life downstream.

(vii) For ground-water recharge and prevention of saline water intrusion to the aquifer, quality of the treated waste water should be close to drinking water standards. The natural purification that occurs during percolation through the soil should not be counted upon without adequate research work. If the ground water gets contaminated, it is a mammoth, if not impossible, task to purify it again, incurring tremendous cost. Therefore, it is preferable to be cautious while using the treated waste water for the above purposes, particularly if that particular aquifer supplies ground water for domestic uses.

(viii) The necessary precautions to be taken on the reuse of treated effluents must be presented to the public through the information media.

In general, one is brought to the conclusion that waste-water reuse has a promising future in the ESCWA region, and that the member countries should start to adopt this practice as a serious alternative to conventional sources of water, if they have not already done so.

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## C. Waste-water reuse in industry

by Georges Pauthe*

### Introduction

Industry is a large consumer of water; sometimes it may be a producer, but for the most part, the balance is negative. Whatever the nature of the production may be, the three following kinds of water are always found: cooling water; domestic and drinking water; and industrial water. Water in each use category has to satisfy specific quality requirements, defined by physical, chemical or biological parameters. The main aim is to determine if there is a problem of water scarcity, to determine the quality of water, and to find to what extent it can be reused, with or without some complementary treatment to satisfy the given need.

This report considers the reuse of waste water only when the second use is different from the first. For example, the reuse of municipal and then industrial waste water in industry are discussed. Thus, the question of "recycling", which implies the same use, and which is developed within the process, is not considered.

Examples are given of water reuses that have already been implemented; the advantages and constraints of such reuses are then considered.

### 1. Municipal waste-water reuse in industry

Most of the water is reused for cooling purposes, material washing and transport and boiler feed water.

#### (a) Industrial cooling

The industrial activities most directly concerned with this kind of reuse are those using an especially large amount of cooling water. In this category are thermal power stations and steel works. The municipal waste water reused has usually gone through a secondary, generally biological treatment.

For water to be used for industrial cooling, two main questions must be addressed; encrustation and corrosion on the one hand, and biological development on the other. To avoid encrustation and corrosion, the pH must be held around 6.5 to 7 so that it allows a high concentration of salts without precipitation. At the same time, inhibitors must be added to prevent corrosion. Other ways, generally more sophisticated, may prevent encrustation and corrosion but, from the operating point of view, this one is the easiest and the most economical. To regulate pH and total alkalinity throughout and at each point of the cooling system is really quite difficult.

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The heavy aeration and high temperatures on the one hand, and presence of nutrients such as nitrogen and phosphorus on the other, tend to produce biological growth. To prevent this, bactericides and fungicides must be added to the water. Chlorine is often added as a disinfectant. The injection may be intermittent in order to increase the efficiency of the treatment.

The following two examples illustrate reuse for industrial cooling. At the thermal power station, Croydon, England (4 units of 52.5 MW) municipal waste water is used for cooling. The capacity of the cooling towers is 66,000 $m^3$/h. Simple filtration is a sufficient complement to the municipal plant biological treatment.

The Normandy Metallurgic Company factory at Caen, France employs 5,000 people and produces about one million tons of steel per year. Its water supplies come from: ground water, 6 million $m^3$; treated waste water (Caen treatment plant) - 1.5, 0.5 and 1.0 million $m^3$ for 1982-3-4; and rain water collected from the factory surroundings.

Before reuse, waste water percolates through a simple filter and is then used in the semi-closed cooling circuit of coke ovens and the steel unit. The quality of the water coming from Caen is systematically controlled, and the engineer keeps in close touch with the plant operator, so that when a waste water quality problem occurs, withdrawal is stopped.

(b) Material and solid wastes transport

This use does not require high quality water, and reuse is possible either directly after the secondary treatment or after a light tertiary treatment. An example is the thermal power plant at Le Havre, France, which uses water from several sources: sea water for the open cooling system; industrial water for the steam boiler; good quality water for drinking; and a treated municipal waste water (300 m3/h).

Waste water is used first for the hydraulic transport of fly ash (produced by the burning of coal) which drains to a sewage farm 8 km from the plant. The water is acidified to prevent corrosion (the ashes contain 4 to 5 per cent of lime, $Ca(OH)_2$, which if not neutralized would induce a partial decarbonation and encrustation. Apart from hydraulic transport, waste water is also used to extinguish the furnace ashes (1,200 $m^3$/day) and for miscellaneous washings (1,200 $m^3$/day).

Two other examples of waste water reuse can be cited. The first concerns transport of gypsum (a by-product of a phosphoric acid manufacturing unit) in Bristol, United Kingdom. The second concerns transport of limestone in a cement plant near Rugby, UK.

(c) Material washing

At Les Graves de l'Estuaire near Le Havre in France, the plant screens, washes, and crushes gravel derived from sea dredging. It uses about 200 $m^3$/h heated waste water from Le Havre's treatment plant, which is discharged into the sea after settling.

## 2. Reuse of industrial waste water in industry

This section describes developments or plants connected with industrial waste-water reuse within the same plant. The examples have been chosen from different industries.

### (a) Dairy works

The following information is derived from a study dealing with a sample of 35 French dairy works. In the aggregate, those works withdrew 15 million $m^3$/year divided up as: 57 per cent for cooling; 6 per cent for heating; and 37 per cent for processing water.

The same works reused 1.45 million $m^3$/year and recycled 26.60 million $m^3$/year. Thus, the utilization rate was about 2.89.

In the process of preparing the product, there are four steps:

(i) Product storage, needing cooling and washing water;
(ii) Thermal treatment, involving both heating and cooling;
(iii) Manufacturing, which needs washing water either for apparatus or for products;
(iv) Packaging, which needs washing water.

In dairy works there are three main uses for water: cooling, using cold water or ice, or both, one after the other; the direct use of steam or cold water heated by steam; and processing, using very high quality water to wash products or apparatus, or not particularly high quality water used for external washing.

Fourteen projects were begun in 1980, some of which are now fully developed. They are divided as follows: nine of cooling water reused for washing; two of heating water reused for washing; four of concentration water used for boiler feeding; one of the reuse of treated waste water.

The study has shown that difficulties in reuse stemmed from two main causes:

(i) The decay of the plant, resulted from successive modifications which induced a geographical scattering, inside the plant, of apparatus using large amounts of water.

(ii) The need for instantaneous availability of water, and because the different uses are not simultaneous, it became necessary to build large storage capacity with the problems of space, investment cost and water treatment.

On the other hand, some factors encouraged the firms to reuse water, such as the scarcity of the resource, the high cost, and the water savings as a consequence of energy savings.

(b) Other food processing examples

The main possibility for water recycling or reuse in sugar refineries is to use evaporation water for diffusion and washing. In one particular case, a syrup distillery is located downstream from the sugar refinery. The steam produced by concentration is used to water down the syrup before fermentation, and to feed the steam boiler.

Two other experiments can be summarized. The first concerns a slaughter house where treated waste water is reused to wash the cow shed. The second is fruit juice concentration, where the concentration water is used to transport and wash the fruit, and to produce steam.

(c) Chemical industry

This case study concerns a fertilizer plant on "Ile de France", an area having scarce water resources. In this plant, domestic water and sewage from the canteen are treated using biological disk systems. Then they are mixed in a large reservoir with other waters derived from the last rinsing resins, condensed steam, filter washings, and rain. Then they are pumped and treated by screening; passing through a hay filter; sterilization with disinfectant; flocculation and filtration; and injection of corrosion inhibitors. In 1983 this treatment allowed reuse of 80 per cent of topping-up cooling water, 650,000 $m^3$/year.

Other qualitative examples of water reuse in the chemical industry are:

(i) Last rinsing water used for first washing water;
(ii) Washing water from mixing machines used as a raw material, suchas when the final product is an aqueous phase, e.g., the paint industry;
(iii) Recycling wash water from the granulator and drier in a fertilizer plant.

These are especially suitable developments as they allow reuse of water, decreased pollutant flow, and improved productivity of the plant.

(e) Oil refinery

The Elf refinery in Grand Puits, France, reuses oily waters (after activated sludge treatment), and rain water. Before reuse for cooling and washing, water passes through a hay filter to a reservoir (40,000 $m^3$), from where it is pumped through filters. For cooling, biocides are added. Because of the addition of ferric chloride, the chloride level in the water may reach 300 mg/l. In 1984 ground-water withdrawal was 1,580,000 $m^3$ per year and reuse was 700,000 $m^3$.

Another example is Mobil Oil's refinery at N.D. de Granvenchon, France (near Le Havre) where most of the treated waste water is reused for cooling and washing purposes. To achieve this reuse, separate treatment of ballast sea water and other waters is necessary to prevent corrosion.

## 3. Advantages and drawbacks

### (a) Technical aspects

In considering municipal waste-water reuse in industry, it is not so much a question of drawbacks as of constraints, in establishing such reuse.

A new sub-structure has to be set up. This includes five elements:

(i) A system is needed to deliver waste water from the municipal treatment plant to the industrial unit for its specific use;

(ii) A storage reservoir is needed to prevent water shortage between needs and availabilities;

(iii) A treatment system to varying degrees is needed according to the quality of the water and its future reuse.

(iv) Special monitoring systems are needed;

(v) The origin of reused water renders its characteristics very inconsistent, especially municipal waste water. It is fitting to monitor carefully and to keep contact with the producer, so as to be quickly aware of problems.

In case of prolonged failure of municipal treatment, some industries may be forced to decrease or even to cease their activities when an alternate feeding water system has not been foreseen.

### (b) Economic aspects

Technical advantages and drawbacks have economic and financial implications.

Where a sub-structure has to be set up, there are investment expenses. As for operation and maintenance, there are costs for energy, labour and reagents. Sometimes, water reuse may allow recovery of final products.

Giving greater yields over and above these parameters, the cost of water, considered as a raw material, has to be taken into account, this cost being higher where the water is scarce.

However, it is very difficult to draw comparative balances and general conclusions. Indeed, the economic conditions are very different and, for instance, costs of energy, labour, reagents, on the one hand, and the cost of water, on the other hand, are quite different. So each case must be studied in its own economic context.

### (c) Environmental aspects

As far as the reuses are concerned, in most cases, the water requires complementary treatment: consequences are obviously advantageous considering pollutant flow discharged. Water resources reuse is important; it contributes to ensure a coherent management of water resources, allowing the saving of top quality water for the more essential uses.

## D. Waste-water reuse for irrigation and aquaculture

by Saul Arlosoroff*

### Introduction

Since the late 1970s, the World Bank has conducted research and analysis on appropriate technology options for water supply and sanitation in developing countries. The technological and economic findings of this programme are being implemented in a number of World Bank and United Nations Development Programme (UNDP) rural and urban projects in Africa, Latin America and Asia. The findings revealed a need for a project that would concentrate on the research and demonstration of resource recovery (waste recycling) activities; such a project was undertaken in 1981 with UNDP collaboration and support from a number of leading bilateral agencies and donor governments. One of the means of resource recovery being investigated as part of the project is waste-water irrigation. This paper describes the global project and specifically deals with health and technology aspects of irrigation with sewage effluents.

### 1. World Bank/UNDP Integrated Resource Recovery Project

#### (a) Background

Materials become wastes when their owner gives them away or pays to have them hauled away. The essential decision with respect to waste management is whether to dispose of the wastes or to retain the remaining values in them. That decision must be made at all levels of society--household, municipal, and industrial--because people usually introduce more materials into their communities than they remove. The goal of waste management and recycling is to conserve resources, including the community space and environment that the wastes would otherwise pollute.

Resource recovery systems and practices have long been established in different parts of the world; however, many of the systems have failed. These have been primarily single-purpose systems, such as those used in producing compost from household garbage, refuse-derived fuel from urban refuse, building materials from fly-ash, and others. The principle problems here have been the high costs of financing, operating, and maintaining complicated "state-of-the-art" equipment, combined with insufficient demands for the products. In contrast, other single-purpose systems--such as using waste-water for irrigation, producing energy from anaerobic digestion, or remanufacturing automotive components--have been relatively successful.

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Overall, an estimated 1 to 2 per cent of the urban populations in developing country cities have come to depend on the value of materials salvaged from solid wastes. Furthermore, people in fringe areas often use the urban sewage in permanent or seasonal irrigation and make use of raw, composted or digested sludge or nightsoil. However, many of these practices have had adverse health, environmental and social effects. In addition, waste management is expensive, with many developing country cities spending over 30 per cent of their disposable income on refuse collection and disposal alone. Solid and liquid domestic, commercial and human waste management have therefore become major municipal expenditures.

Among the integrated systems that have been recognized as successful are the Shanghai Resource Recovery and Utilization Company and Rome's Sorain-Cecchini facilities. These systems have demonstrated the efficiency of integrating industrial and post-consumer scrap, household and community wastes, resource recovery technologies, and/or recycled product utilization. An essential determinant of success has been cross-sectoral financial and institutional integration, the importance of which will undoubedly increase as urbanization proceeds in developing countries. Such integration helps to reduce the costs of environmentally acceptable waste disposal through the recycling of recoverable resources.

In today's world, urban space is limited, expensive, and easily polluted. The conventional approach to handling wastes is to collect those wastes that would otherwise cause a myriad of small, dispersed environmental problems and combine them into a single, large, concentrated environmental problem. Centralized sewage and refuse collection systems are designed to get the wastes off the street; they reduce the affected area but not the mass of pollution problems. Their annual capital recovery costs are sometimes 2 to 4 times the operation and maintenance costs. The total financial costs for sanitation and sewerage range from about 1.2 to 7-8 times the cost of water supply, depending on the level of water service. The higher values reflect the costs of collection and treatment. Note that, in many cases, the costs of sewage treatment are derived not from getting the solids out of the water but from getting the water out of the solids. Similarly, high costs are incurred, for example, in separating glass from the much larger volume of municipal mixed refuse. At present, the ratio of disposal to supply costs for solid materials and products is reversed because the supply costs are much higher and because low priority is given to the control and recycling of the toxic components in these materials. Even so, the total costs for solid waste disposal are generally higher than those for sewage disposal. These costs are determined by the particular service levels and technologies selected.

The rationale for waste recycling rests on a number of factors, particularly: (i) the depletion of readily accessible high-quality sources of energy, water, soil nutrients, space and material resources; (ii) the financial, institutional, and political needs for resource self-sufficiency; (iii) the increasingly higher costs of waste management and conventional pollution control, particularly those from toxic wastes; (iv) the need to conserve much of the original energy, material and labour values added to water and other materials that are otherwise wastes; and (v) the growing scarcity of foreign currency in many of the developing countries.

(b) Goals and objectives of the Integrated Resource Recovery Project

The goals of research and development in the Integrated Resource Recovery Project (UNDP/GLO/80/004) are: (i) to promote and lead towards health, economic and financial benefits through resource recovery and utilization projects in developing countries; and (ii) to assemble, assess, and disseminate technological and economic data and infromation to developing countries embarking on resource recovery.

Specific objectives stated in the original project document are as follows: (i) to conduct and document state-of-the-art reviews of resource recovery technologies; (ii) to conduct and document case studies on technological, environmental, institutional and economic aspects of entrepreneurial and community systems for waste collection, and refuse and resource recovery projects adapted to specific conditions of urban areas of lower- as well as higher-income developing countries; and (iii) to monitor and evaluate the initial operations of demonstration projects and promote full-scale investment projects in integrated resource recovery and utilization which will result in reduced costs of community sanitation and waste management.

The principal categories of research and development undertaken under GLO/80/004 include (i) inorganic materials recovery; (ii) organic materials utilization; (iii) waste-water reclamation; (iv) energy savings and production; and (v) land reclamation.

For project management purposes, a technological classification of six project activities has been promulgated: (i) waste-water irrigation; (ii) wase-water aquaculture; (iii) advanced technology thermophilic biogas and slurry production and utilization; (iv) landfill gas utilization; (v) inorganic materials recovery; and (vi) co-composting of nightsoil, garbage, and other organic wastes.

(c) Status, Scope and Approach of the Project

During the research and development phase, international and host-country consultants have been commissioned to prepare a number of generic and case studies. Generic (generally global) reports on resource recovery from municipal solid wastes, anaerobic digestion, health effects of waste water irrigation and their control, ultimate disposal of waste water to the ocean, waste-fed aquaculture and a technical framework for economic analysis of waste recycling and disposal have been completed and will soon be published. Other reports on co-composting, landfill gas and other topics will be published at a future time. These and selected case-study reports are scheduled for publication in 1985 to 1987.

Case studies have been conducted or initiated in 25 communities in 15 developing countries (Brazil, Cameroon, China, Cyprus, Egypt, Ghana, India, the Ivory Coast, Mexico, Nepal, the Philippines, Peru, Sri Lanka, the Sudan and Thailand). In addition, the status of municipal operating recycling facilities in various European countries has been surveyed to identify the technologies most suitable for transfer to developing countries. The information in the case studies has been obtained at three levels:

(i) An engineering survey of present and potential waste sources, management, and recycling activities or systems. Special attention is given to household, community, and environmental sanitation systems, which are considered to be important elements of resource recovery project activities. Criteria used in selection of sites for further study include appropriate resource recovery technologies to be considered, assurance of local and central government support to the projects, and identification of potential bilateral and multilateral collaboration and cofinancing.

(ii) A multidisciplinary study of institutions, financing, technologies, utilization, and possible integration of waste recycling activities at sites selected from the original list.

(iii) Identification, preparation and implementation of demonstration at 4 to 6 sites, including Shanghai, Kathmandu, Lima, Bangkok, Cyprus and India, subject to funding from donor agencies. Systems being considered for demonstration include waste-water irrigation and/or aquaculture, small-scale landfills and land reclamation, the marketing of compost and other recycled materials, and the recovery of industrial and post-consumer organic and inorganic materials.

(d) Initial project conclusions

Data from three years of global research and development lead to the following initial conclusions:

(i) Integrated recovery and institutionalization of urban solid and liquid wastes management can reduce waste management costs to municipalities by 30 to 50 per cent. Since waste management costs in developing country cities often account for 30 to 50 per cent of municipal budgets, these potential savings are significant. They will become even more important in the future as efficient urban waste management services are extended beyond the present estimated 20 per cent of urban populations served.

(ii) Economic benefits of recycling are revealed by, for example, the employment of one to two per cent of urban populations in secondary materials enterprises and seasonal irrigation, using the sewage from developing country cities.

(iii) Potential environmental and health effects of waste collection and disposal can be economically controlled by appropriate recycling technologies.

(iv) Institutional and social constraints to recycling can be identified and dealt with.

(v) Selection of an appropriate resource recovery technology and system is site-specific and depends upon waste quantities and characteristics, envionmental and economic policies, scale of industrialization, and the potential demands for recovered resources.

## 2. Health effects of waste-water irrigation and their control in developing countries

Ancient and current systems for using human waste in the production of agricultural products have evolved in response to environmental and economic imperatives. The development of sewerage systems introduced an additional resource--water--into many of these systems which operate in areas of permanent or seasonal drought. It is estimated that some 60 to 80 per cent of the waste water from the cities in developing countries is currently used for irrigation. This has led the GLO/80/004 Project to commission a team of consultants from the Hebrew University of Jerusalem, who have worked on the issue in Israel and elsewhere for 15 years, to conduct a study on the related health, technological, and agronomic issues in waste-water irrigation, with the aim of developing an environmentally-sound investment policy for waste-water reuse in agriculture.

Conventional public health opinion and policy assumes that the detection of the broad spectrum of enteric pathogenic bacteria, viruses, protozoa and helminths found in the waste-water stream of a community or on waste-water irrigated crops is sufficient to indicate that a public health problem exists and that such evidence points to a real potential for disease transmission. Very strict health regulations have therefore been established in the Unied States and other industrialized countries which generally allow for the irrigation only of non-edible crops with primary effluent and require meeting strict water quality standards, approaching those for drinking water, if vegetable and salad crops are to be irrigated with effluent. Examples based on this strict approach are the standards of the Department of Health of the State of California and the guidelines of the World Health Organization shown in table 32 above (Chapter IV B). Little effort has been made in the past to justify or validate these standards with firm epidemiological evidence. It has been assumed by some developing countries and international agencies that the strict public health approach to the regulation of waste-water reuse in agriculture which has evolved over the years in the industrialized countries is equally applicable to the developing countries.

One of the primary goals of this UNDP/World Bank study has been to carry out a rigorous, critical review and evaluation of available documented epdemiological evidence with the aim of determining the significant, quantifiable, health effects on population groups directly or indirectly exposed to waste-water irrigation: by working with or around the waste water; by residing in contiguous communities; or by consuming waste-irrigated crops. The implication of these findings for the special health conditions that exist in the developing countries has been evaluated.

Based on these findings, an evaluation of costs and benefits of various remedial measures appropriate for developing countries has been carried out. Technological and policy options for governments and development agencies have been proposed which facilitate sustainable systems of waste-water irrigation. These should enable countries to achieve the optimal social and economic benefits from the increased water resources for agricultural development, the recycling of nutrients to the soil and the reduction of pollution to surface bodies of water, while assuring appropriate control of potential negative health effects.

(a) Intervening Factors

An extensive review of the literature on the concentration and survival of pathogens in waste water, soil and air and on crops has been carried out. The main conclusion from this review is that the waste waters from urban areas carry the full spectrum of fecally-excreted human pathogens endemic in the community, including helminths, protozoa, bacteria and viruses. Their concentrations are sufficiently high and their persistence in generally unfavourable environments (with sunlight and drying) is sufficiently long in the waste-water-irrigated soil and crops to allow theoretically for the infection of exposed population groups. Figure 24 shows the estimated average persistence of selected enteric pathogens in waste water and soil and on contaminated crops at 20 to 30 degrees Centigrade. Most enteric pathogens can therefore survive in the environment for weeks or months and some for up to a year.

Infection of humans, however, does not result from the mere presence of pathogens in the soil or on edible crops. A number of intervening factors control the possibilities of human infection. The minimal infective dose of a pathogen required to cause infection or human disease varies greatly. Some, such as helminths and viruses, can cause infections in a susceptible host through a single organism, while others, such as Salmonellae, will cause infection or disease only if many millions of organisms are ingested. Figure 25 illustrates typical minimal infective doses for various enteric pathogens based on numerous studies with human volunteers. Actual infective doses may be lower in infants or adults suffering from malnutrition or immunologically compromised.

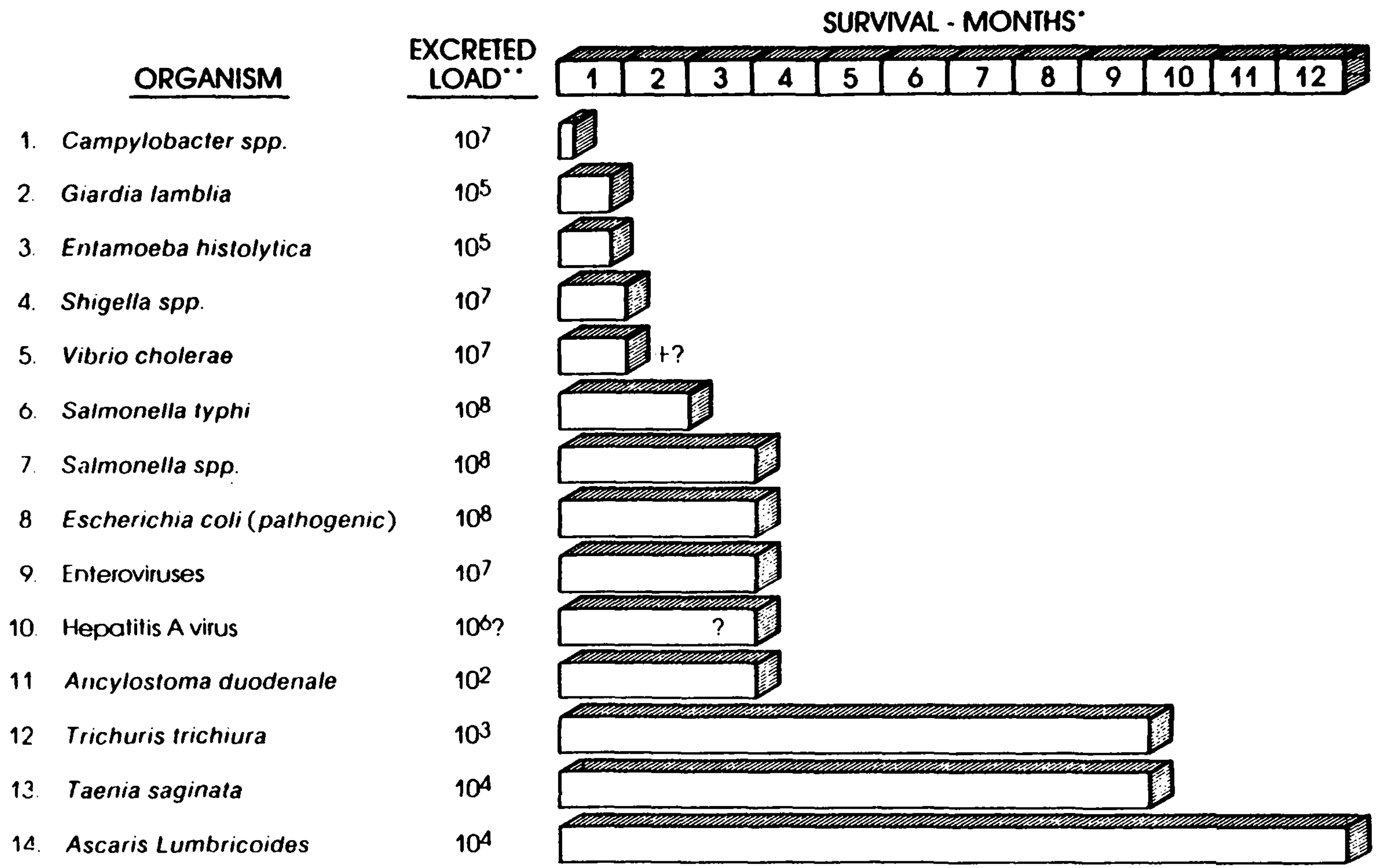
The level of human immunity to endemic diseases is also an important factor. Some pathogens, such as enteroviruses, are so infective and so common in the household environment of the developing countries that most infants acquire lifelong immunity at an early age. In many developing countries, multiple routes of concurrent infection by enteric pathogens (from contaminated water and food and poor personal and domestic hygiene) may make uncontrolled waste-water irrigation an insignificant cause of excess disease. The role of these and other intervening factors must be carefully considered in evaluating and interpreting the epidemiological evidence.

(b) Epidemiological evidence as to quantifiable health effects associated with waste-water irrigation

General conclusions from initial pertinent studies investigated as part of the project are as follows:

(i) Population groups consuming vegetables and salad crops irrigated with raw waste water

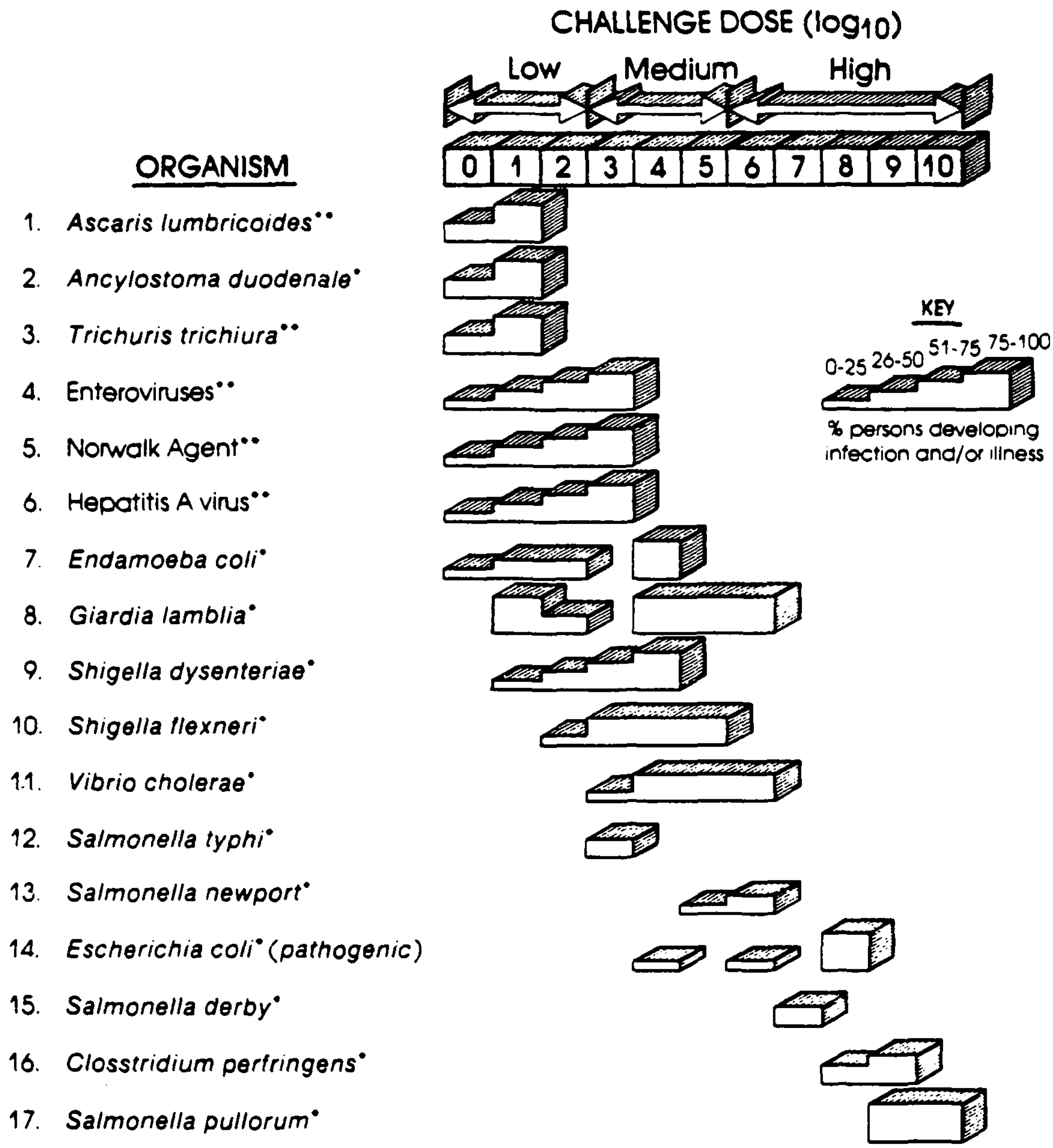
In those areas of the world where the helminthic diseases caused by Ascaris and Trichuris are endemic in the population, and where raw, untreated waste water is used to irrigate salad crops and/or other vegetables generally eaten uncooked, one of the important routes of transmission of these infections to the general population can be through the consumption of such waste-water-irrigated salad and vegetable crops.




* Estimated average life of infective stage at 20°-30°C

** Typical average number of organism/gm feces (after Feachem et al, 1983)

Figure 24. Persistence of enteric pathogens in the environment: water, soil or crops




* After EPA-600/1-79-0160 (pgs. 444-447)
** Estimated from various sources

Figure 25. Minimal infective dose of enteric pathogens

A study from Darmstadt, Germany provided evidence on this point (see figure 26). Thus, it appears that, both in areas of relatively high levels of municipal sanitation and personal hygiene and areas of much lower levels of municipal sanitation and personal hygiene, irrigation of vegetables and salad crops with raw waste water can serve as a major pathway for the continuing and long-term exposure of the population to Ascaris and Trichuris infections. Both of these infections are of a cumulative, chronic nature where repeated long-term reinfection leads to an increase in the individual's worm load and an increase in the possibility of negative health effects.

Cholera can also be transmitted by vegetable and salad crops irrigated with raw waste water carrying cholera vibrios to populations consuming such vegetable products.

There is only limited epidemiological evidence indicating that beef tapeworms (Taenia saginata) have been transmitted to populations consuming the meat of cattle grazing on waste-water-irrigated fields or fed crops from such fields. There is strong evidence that cattle grazing in fields freshly irrigated with raw waste water or who drink from raw waste-water canals or ponds can become heavily infected with the disease (cysticerosis).

(ii) Health effects among sewage farm workers

Sewage farm workers exposed to raw waste water in areas where Ancylostoma (hookwork) and Ascaris infections are endemic have been shown to have significant excess levels of infection of the two as compared to other agricultural workers in a similar occupation (figure 27). The risk of infection with hookworm is particularly great in areas where farmers customarily work barefoot; however, even more importantly, the intensity of the parasitic infections (the number of worms infesting the intestinal tract of an individual) of the sewage farm workers was greater than that of the controls. Another important finding was the greater number of sewage farm workers suffering from anemia--one of the typical debilitating symptoms of severe cases of hookworm infestation. This is evidence of the direct economic impact on human productivity which can result from continuing occupational exposure to irrigation with raw waste water.

Sewage farm workers may become infected with cholera if irrigating with a raw waste-water stream derived from an urban area suffering from a cholera epidemic.

There is only very limited and often conflicting evidence as to the adverse health effects from bacterial and virus diseases among waste-water irrigation workers or waste-water treatment plant workers similarly exposed directly to waste water or to waste-water aerosols. It is hypothesized that, in general, sewerage farmers or treatment plant workers have acquired relatively high levels of lasting immunity to most of the common enteric viruses endemic in the community at a much younger age, and thus, by the time they are exposed occupationally, the possibility of disese or other detrimental health effect is small.

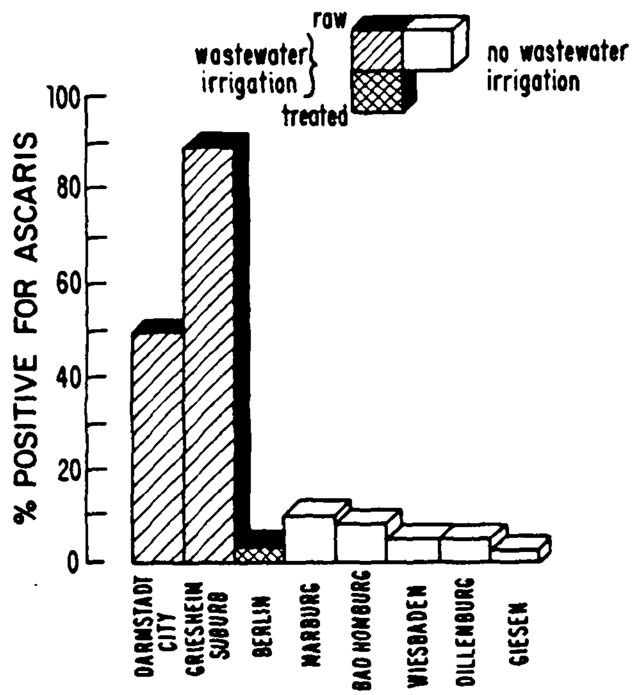



Figure 26. Waste-water irrigation of vegetables and Ascaris prevalence in cities of the Federal Republic of Germany

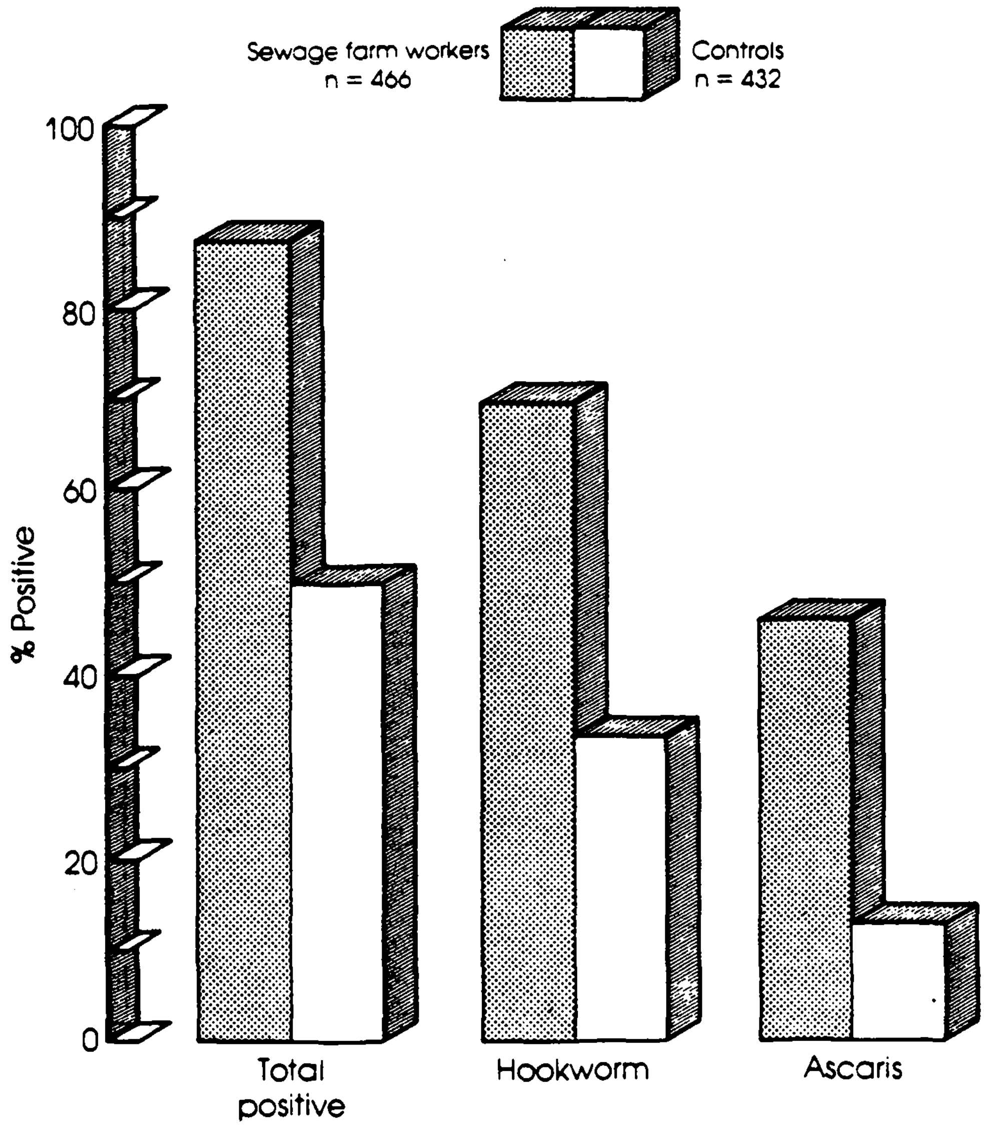



Figure 27. Prevalence of parasitic infections in sewage farm workers and controls in India

(iii) Health effects among population groups residing near waste-water irrigated fields

Evidence as to disease and/or infection in population groups residing near waste-water treatment plants or waste-water irrigation sites has generally provided negative results. Most studies have not shown any demonstrable infection as a result of the dispersion of aerosolized pathogens by such processes; however, it was agreed by the researchers that most studies to date were inadequate. Findings provide support for the conclusion that, in general, the relatively high levels of immunity against most viruses endemic in the community essentially block environmental transmission by waste-water irrigation, and keep it at such a low level that the additional health burden is not measurable. Thus, the primary route of transmission of such enteroviruses, even under good hygienic conditions, is through contact infection at a relatively young age. As stated previously, such contact infection is even more intensive in developing countries, and waste-water irrigation practices would probably not be expected to result in any meaningful added health problems as far as viruses are concerned.

(iv) Reduction in negative health effects by waste-water treatment

Based on credible epidemilogical studies, evidence as to the reduction of negative health effects from effective pathogen removal after waste-water treatment is limited. Data from those few epidemiological studies conducted thus far do not provide conclusive evidence as to the health benefits to be gained by effective pathogen removal by waste-water treatment. The data do converge, however, with water quality data on pathogen removal and lead to the conclusion that appropriate waste-water treatment, resulting in effective removal of priority pathogens, can indeed provide a high level of health protection.

(c) When epidemiological evidence is absent

The conventional public approach argues that all excreted enteric pathogens with sufficient persistence in the environment could, at some time, be transmitted by irrigation with raw waste water. This may indeed be so, and we cannot rule out the possibility that other enteric diseases with a known record for environmental transmission (and water-borne transmission in particular) may also, at times, be transmitted by uncontrolled waste-water irrigation. The diseases that are potentially associated with irrigation with raw sewage include typhoid fever, infectious hepatitis, bacillary dysentery, rotavirus infection, enteroviral infections, amoebiasis, giardiasis and possibly other enteric diseases.

The lack of firm epidemiological evidence may be due to several factors, including: the lack of resources, including research capabilities and/or priorities for carrying out credible epidemiological field studies in areas where waste-water irrigation is practised; the general difficulty in obtaining adequate, well-matched control populations for comparative studies; and the difficulty in demonstrating statistically significant differences in studies of environmentally transmitted diseases being transmitted simultaneously by multiple routes. In developing countries, other routes of transmission, e.g., contact resulting from low levels of personal and domestic hygiene and contamination of water and food, are usually so dominant for these diseases that any excess infection due to waste-water irrigation is not detectable even in the most sophisticated and well-designed epidemiological study. In contrast, countries with high levels of hygiene and generally safe water supplies are assumed to be susceptible to bacterial diseases from irrigation of salad crops with raw waste water.

(d) Implications for developing countries

From the foregoing analysis of epidemiological studies from both developed and developing countries on the health effects of waste-water reuse in agriculture, we conclude that there is evidence of occasional transmission of diseases associated with the use of raw or only partially treated waste water. For the developing countries, the evidence on disease transmission associated with waste-water irrigation points most strongly to the helminths as the number one problem with some limited transmission of bacterial and virus disease. It can be assumed that, in most developing countries suffering from low socio-economic conditions and poor levels of personal and domestic hygiene, the population is exposed to, and has become immune to, the endemic enteric virus diseases at a very young age through typical contact infection in the home.

The vast majority of infections with enteroviruses lead either to benign short episodes of acute illness or to subclinical infections having little impact. Some virus infections such as rotavirus, however, play a major role in high infant mortality rates. For most of these diseases, lifelong immunity is acquired at a very young age, so that there can be no more than one episode of any particular enterovirus disease in a lifetime. While the number of potential enteroviruses that can cause infection through the faecal-oral route or through contaminated waste water is rather large, reaching approximately 100 discrete pathogenic viruses, in most developing countries the excess virus infection resulting from waste-water utilization practices is nil or insignificant.

In contrast to enteric viruses, there is little or no immunity in man to most enteric protozoa or helminths. Each worm egg ingested can lead to the infection of the intestinal tract by an addition of one parasitic worm; therefore, with continuing exposure, the infestation is long-term and cumulative. Population groups constantly exposed to Ascaris, Trichuris, or Taenia infections through the consumption of waste-water-irrigated vegetable crops or consumption of meat from animals raised on waste-water-irrigated fields can be expected to carry ever-increasing loads of these helminths in their intestinal tracts for long periods of time (or for as long as they are exposed to the contaminated crops). Similarly, waste water will build up heavy, debilitating hookworm loads carried in their intestinal tracts. For all these reasons, the danger of transmission of helminth disease by waste-water use in agriculture appears to be the number one problem for the developing countries.

For most developing countries suffering from relatively low levels of personal and domestic hygiene, it can be assumed that, as with virus diseases, most transmission of bacterial enteric diseases takes place through direct contact infection or through contaminated water or food. While a few enteric bacterial diseases impart long-term immunity, most result in relatively short periods of immunity, if any at all. Nevertheless, under conditions of intensive endemic transmission, a significant proportion of the population may have transient immunity to specific bacterial diseases at any given moment, thus reducing the opportunity for further infection and diseases from external environmental factors. Cholera, bacillary dysentery, typhoid, and possibly other bacterial enteric infections can be transmitted by waste-water irrigation in industrial countries. In contrast, we can assume that in developing countries where these diseases are endemic with concurrent multiple routes of transmission, any additional transmission by waste-water irrigation would cause little, if any, additional health burden and would not be detectible by epidemiological methods.

In conclusion, we would rank pathogenic agents in the following declining order of priority for the developing countries.

(i) High risk (high excess incidence of infection): Helminths (*Ancylostoma*, *Ascaris*, *Trichuris* and *Taenia*);

(ii) Medium risk (medium excess incidence of infection): Enteric Bacteria (cholera, typhoid, *Shigella*, and possibly others);

(iii) Low risk (low incidence of excess infection): Enteric viruses.

It must be pointed out that these negative health effects were all detected in association with the use of raw or poorly settled waste water. Therefore, we also can conclude that waste-water treatment processes which effectively remove all or most of these pathogens according to their priority in the above listing could provide a major or total reduction in the negative health effects caused by raw waste-water use. The ideal treatment process should therefore be one that is particularly effective in removing the top priority--helminths--even if less efficient for bacterial and virus removal.

(e) Technical and policy options for remedial measures

Based on the above findings of quantifiable health effects of uncontrolled irrigation with raw waste water, a series of alternative remedial measures have been considered for application in developing countries. The measures are as follows:

(i) Restrictions on the types of crops irrigated, so as to prevent consumers from being exposed directly to infection through contaminated vegetables or salad crops eaten raw.

(ii) Selection of irrigation techniques and procedures so as to prevent or minimize direct contact between waste water and crops.

(iii) Improved occupational health and hygiene conditions.

(iv) Disinfection of crops susceptible to contamination in central market facilities or in the home.

(v) Chemotherapeutic and/or prophylactic medical treatment to protect or cure sewage farm workers or consumers of waste-water-irrigated crops of the diseases or effects of the diseases associated with waste-water irrigation.

(vi) Waste-water treatment and/or storage practices aimed at effectively reducing the concentration of the priority pathogens to initially low levels, and, in subsequent stages, to levels below which the incidence of excess infection is essentially controlled.

(vii) Integrated, site-specific combinations of the above responses.

Crop restrictions and modifications of irrigation techniques have been highly effective in reducing infection from waste-water irrigation in technologically advanced countries with long traditions of civic discipline and effective law enforcement. Such regulations can be effective on centrally-managed sewage farms or irrigation districts. The success of such crop regulations at the 40,000-hectare Irrigation District 03 near Mexico City is an example. Farmers who do not comply with crop restrictions may face sanctions, including losing their water rights. Such regulations would be more difficult to enforce with a large number of small subsistence sewage farms located along the urban fringe of developing country cities.

Improved occupational hygiene conditions for sewage farmers such as special areas for eating with hand-washing facilities, and the supply of boots to protect feet from direct contact with waste-water-irrigated soil, can be applied only in well-organized and centrally-managed farms. This option is difficult to apply to numerous individual small farms.

Washing and disinfection of crops in markets of households could be introduced through health education in communities with high levels of education, but is only of limited effectiveness as a general preventive measure. Central vegetable disinfection stations would be limited to those vegetables whose freshness and appearance would not be damaged.

Prophylaxis and/or mass chemotherapy of persons exposed to continuing helminth reinfections are not generally accepted by the public health professions. It may be effective as an interim measure during initial stages of a programme to reduce infection where subsequent measures include improved waste-water treatment. This could be combined with mineral iron dietary supplements which are considered to be effective in ameliorating the severe anemia due to heavy hookworm infections, but does not cure the individual from his infection. It would not reduce the other clinical effects and discomfort from the disease.

Only waste-water treatment effectively removes helminths and provides an acceptable reduction of pathogenic bacteria and viruses, while simultaneously reducing the overall excess infection due to occupational and consumer exposures. Clearly, acceptability of treatment systems which achieve any given degree of bacteria and virus removal will depend upon health profiles, immunities, and investment priorities of the populations who are to be protected.

(f) Appropriate waste-water treatment technology

The priority criteria for effective waste-water treatment for agricultural irrigation in developing countries are as follows: (i) maximum removal of helminths; (ii) effective reduction in bacterial and viral pathogens; and (iii) freedom from odour and appearance nuisances so that the effluent is attractive for agricultural use (i.e., effective reduction of biochemical oxygen demand or BOD).

These specific design criteria and their order of priority differ from those for reducing surface water pollution from BOD and chemical oxygen demand (COD), thereby resulting in different optimal treatment strategies. Conventional waste-water treatment plants, in spite of their greater costs, utilization of mechanical equipment, and large energy inputs, are not particularly effective in meeting the first two criteria. In contrast, a series of stabilization ponds with 20 days detention are suited to meet all three criteria and are the system of choice for helminth removal.

Well-designed and operated series of stabilization ponds achieve essentially total removal of helminths, a 99.9-99.999 per cent reduction of enteric bacteria and a 90-99 per cent reduction of enteric viruses. They can produce an odour-free effluent which is rich in nutrients and attractive for agricultural use. They are most suitable in warm developing countries. They have low construction and operation costs and no moving parts and are a particularly robust, almost fail-safe type of treatment system.

An optimal design includes a first-stage anaerobic pond treatment unit, followed by a series of facultative and maturation ponds. An example is a system with one or two days of detention in the anaerobic stage, followed by some 15 to 20 days of detention in four more ponds in series (see figure 28). If there are limited financial resources or limited availabilities of land, construction of a stabilization pond system in stages is feasible. The minimum first-stage would be anaerobic ponds with one or two days detention; the second stage would be facultative ponds, with a detention period of an additional 7 or 8 days. In addition to removing helminths, the system would provide partial removal of enteric bacteria and viruses.

An alternative low-cost system is the classic multi-cell municipal septic tank with two days of detention, which provides adequate volume for combined anaerobic sludge digestion. Although these systems are generally not favoured by design engineers in the industrial countries, the long anaerobic detention periods provide good conditions for the removal of helminths by settling. (These helminths are much less effectively removed by the conventional industrial country waste-water treatment schemes which have replaced community septic tanks in industrial countries.) Municipal septic or similar long-term detention tank systems are much less expensive and simpler to operate than conventional treatment plants and require small land areas. The system does not meet the third-priority design criterion, as it is not completely odour-free and may be physically unattractive. It does meet the first criterion of reducing the risks of helminth infection.

Construction costs of various stabilization pond systems are 25 to 50 per cent of the costs for aerated ponds and 15 to 20 per cent of those for conventional secondary treatment plants. Stabilization ponds followed by

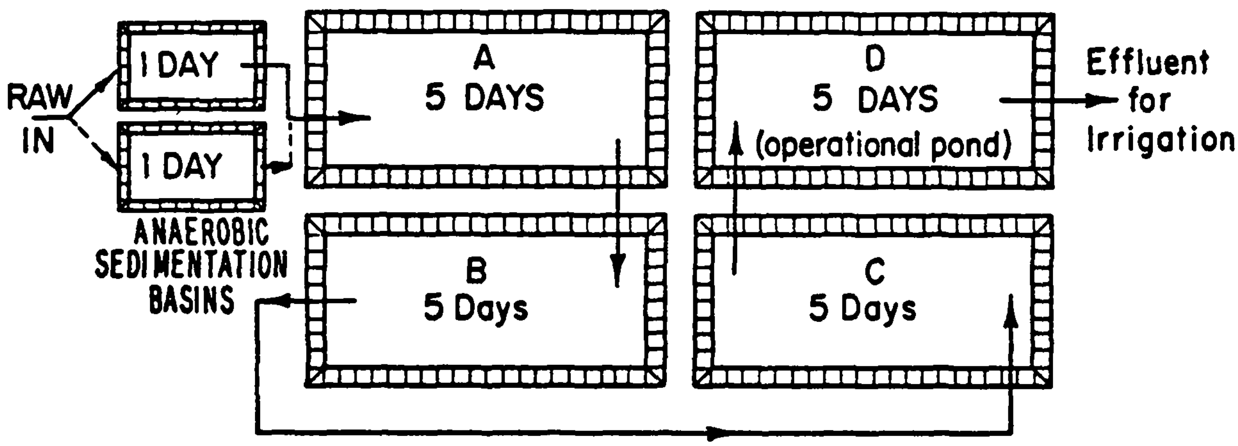



Figure 28. Suggested layout of equally-sized oxidation ponds in series

reservoirs for off-season storage provide increased effluent utilization during irrigation periods, reduce environmental contamination of surface waters, and reduce suspended solids sufficiently, making drip irrigation feasible. The reservoirs may also serve as polishing ponds or ponds for fish or prawn production. In summary, there are a number of engineering options to be considered in selecting the optimum, initial, and final waste-water treatment systems.

Excessive land costs for pond systems are often cited by advocates of conventional primary or secondary sewage treatment systems. In urban fringe or other highly productive areas with ready access to markets, these costs range generally from $US 5,000 to 20,000 per hectare, with most falling between $US 10,000 and 15,000. As urban transportation and other services are brought in, land prices increase 10- or 20-fold. The land requirement for a 20-day pond system receiving 80 litres per capita per day is about one square metre per capita, thus costing approximately one to two dollars per capita.

The fact that the costs of the collection system are much greater than land for pond systems is not an issue. When their values increase sufficiently, pond areas can be sold and additional pipelines and new, more distant ponds can be built. The higher costs of conventional primary and secondary treatment works continue to be avoided. Their operation, maintenance and energy costs overshadow the costs by moving the ponds after a few years of operation.

Smaller communities, particularly those whose boundaries are fixed by topography or are only slowly expanding, present somewhat different situations. The surrounding agricultural land is probably intensively farmed, with resulting land values being high. The options for which the beneficiaries are willing to pay may therefore begin with small-scale anaerobic systems. When sufficient funds are available, investments in larger service area collections, stabilization ponds, and fish-culture systems can be made. In warm climates, routinely-achieved productivity of 5 to 8 tons per hectare per year (which can be doubled with appropriate operation) is ordinarily sufficient to justify the land costs.

An additional advantage of the waste treatment option is the speed with which health benefits can be achieved, as no change is needed in the personal habits and customs of large numbers of people. Systems which require changing lifestyles, customs and personal behaviour require more time and expense. The full environmental and agricultural benefits of a sustainable programme for recycling waste water by agricultural irrigation in developing countries are best achieved by effective, stable, low-cost waste-water treatment which provides immediate and long-term benefits to all affected populations. Such a method will satisfy the health and environmental priorities of helminth, bacteria, protozoa and nuisance removal. Corresponding technical priorities are balancing capacity to demand and selecting interim technical solutions that are robust, easily upgradeable, and capable of extension.

Financial and economic priorities include consideration of alternative technologies and service standards during the early phases of project identification and preparation. This will lead to comparable economic costing, maximization of benefits from each alternative through proper design and operation, and involvement of the users in making the interim and final cost/benefit determinations.

(g) Conclusions on the health effects of waste-water irrigation

The study of health effects of waste-water irrigation and the remedial measures for their control leads to the conclusion that the previous public health orthodoxy which held that every excreted pathogen that can persist in the environment, in the soil or on crops irrigated with waste water is a potential cause of serious disease in a person is basically overly conservative, particularly when applied to developing countries. Credible, quantifiable, health effects of waste-water irrigation which have been identified in this study and applied to developing countries are limited. The priority pathogenic agents, mainly helminths, are almost totally removed by settling for one or two days under anaerobic conditions and completely removed (together with effective reductions in bacteria and viruses) in 15 - 20 days in stabilization ponds by low-cost robust treatment methods suited to the needs of developing countries.

In both permanently and seasonally arid areas, waste-water irrigation has numerous benefits--increased agricultural production, improved food supply and reduced environmental pollution. The total societal benefits of waste-water reuse in irrigation undoubtedly exceed its negative effects, which can be easily controlled by low-cost technologies and closely matched to site-specific waste water, environmental, and health priorities.

## 3. A case study in a Latin American city

(a) A justification of the proposed sewage investment plan for the next 10 years

A large majority of the salad crops and vegetables now eaten in the area of the site are irrigated with untreated sewage. This is undoubtedly a major source for the spread of pathogenic enteric micro-organisms throughout the city. Evidence now exists that it may also be a major cause of the spread of typhoid fever. For this reason, the city is studying proposals for a sewage treatment and disposal master plan supported by the GLO/80/004 Integrated Resource Recovery Project.

A full economic study is required to provide a detailed cost-benefit analysis and justification of the proposed sewage investment plan for the city. The following factors should be taken into consideration in the analysis of the potential benefits of the proposed sewage investment plan.

(i) Value of treated sewage (effluents)

Water is a scarce commodity in the area, particularly during the critical long, dry, summer irrigation period. Although no value has been given to waste water used for irrigation until now, maintaining the social usefulness of the currently recycled water is definitely an economic benefit.

In addition to the value of the water *per se*, sewage effluent carries all of the major nutrients (N, P and K) and many of the important micronutrients required for high levels of agricultural productivity and maintenance of good long-term soil fertility. The value of this component should be calculated as a net benefit to agriculture since sewage-irrigated areas near the city have demonstrated that relatively high crop production can be achieved with no added cost for fertilizers.

The water authority will, at considerable expense, have to increase the amount of water supplied to the city as the population grows to the estimated 8 million by the year 2010. This additional increment of water will be recycled as treated waste water for irrigation and will enable farmers to increase the area of irrigated land. A method of direct recovery of the value of this additional water should be worked out, possibly as a direct cash income to partially cover the costs of the project.

(ii) Reduction in typhoid fever and other enteric diseases

There is a high incidence of typhoid fever, endemic in the city; however, it is reasonable to assume that the true typhoid fever incidence is several times greater than that officially reported by Ministry of Health Statistics. It is not unreasonable to assume that, similar to situations in other highly developed cities, most of the typhoid caused by external sources will be prevented by effective sewage treatment. An 80 - 90 per cent reduction in typhoid can be expected in time. The benefit of eventually achieving a major reduction in the number of cases of typhoid will have to be calculated and based on estimated average medical and hospitalization costs per case and lost productivity due to absenteeism and other social costs.

Although only typhoid has been studied in detail, the city suffers from very high rates of other gastrointestinal diseases. The rates of non-reported clinical gastroenteritis may be over one hundred times that of typhoid. Some of these enteric diseases, such as infectious hepatitis, are serious diseases leading to long medical care periods and absence from work. Others may be of short duration. It should be assumed that sewage treatment will bring noticeable additional economic benefits by significantly reducing the rates of other enteric diseases.

(iii) Tourism

Undoubtedly, the tourist industry will benefit by the reduction in the risk of tourists becoming ill with typhoid and other gastro-intestinal diseases. Eliminating the fear of disease is an important factor in promoting tourism.

(iv) Prevention of major epidemics of high economic impact

Irrigation of salad crops with raw waste water, as now practised in the city, has in at least one other case been associated with an outbreak of epidemic cholera. In that case, the economic damage was far greater than the direct health costs might indicate. International notification of the epidemic to all other countries as required by quarantine regulations resulted in an almost total loss of the entire prime tourist season. Export of fresh fruit and vegetables to Europe, a major export industry, was almost completely halted. Even other industrial exports such as processed food and non-food products were affected. That single outbreak resulted in an economic blow of major proportions to the total national economy. It would only require a few returning tourists who were infected in an endemic area in Asia or Africa to infect the entire sewage stream of the city and possibly lead to a recurrence of the economically disastrous effects of the other epidemic. The investment involved in preventing such a low frequency but high cost risk is an important consideration in the justification of the Sewerage Master Plan for the city.

(v) Imponderables

There are a number of social and economic benefits from the Sewerage Master Plan that are difficult to measure in money terms, i.e., the national pride and self-image of the capital city now suffering from the "spectre" of typhoid and "open sewers" across its centre; and the fear and worry of parents about the health of their children or the danger to their own health.

(vi) Conclusion

The potential benefits from the execution of an appropriate Sewerage Treatment Plan will be direct and meaningful to the population and the economy of the city as well as the entire country. The city suffers from an unusually high rate of typhoid fever, now considered a totally preventable disease. Modern techniques of environmental engineering in the form of appropriate and effective sewage treatment plants, e.g., lagoons, should have an immediate beneficial effect in reducing typhoid and other enteric diseases.

(b) The principles of design and construction scheduling of the proposed sewage treatment works for the city

The report on the Sewerage and Drainage Master Plan for the city is not yet available for detailed review; however, the following are some general remarks on the principles of design and construction scheduling of the proposed sewage treatment works.

(i) Stabilization lagoons--general

The basic recommendation of the consultants' study is to select stabilization lagoons as the treatment method of choice. This method can achieve high levels of removal of pathogenic micro-organisms with stable, robust operation at relatively low costs. Energy consumption is minimal and investment in expensive and difficult-to-maintain mechanical equipment can be avoided. Large stabilization lagoons have been used by some major cities for years (i.e. Melbourne, Australia) and have demonstrated good results. A stabilization lagoon system has been operating in Lima, Peru for a number of years and studies by WHO have shown that the plant has achieved a high level of over-all efficiency in sewage treatment, with particularly good results in the removal of pathogens. The main disadvantage of lagoons is the large land areas required. An economic study must be made to determine if the proposed lagoon system is indeed less expensive than alternatives when land costs are included (for example, aerated lagoons).

Future increases in land values, as urban areas expand and approach the lagoon areas, should not be seen as a negative factor. If at some future date the value of the land greatly increases, it may be justified to sell a portion of the land for urban development and build a high energy and equipment-intensive type of sewage treatment plant which requires less space or move the ponds to another location further away. Postponing the construction of such a plant for as long as is feasible is a desirable objective and will most likely be the wisest investment policy.

(ii) Design criteria for lagoons

The design criteria must be based on achieving the specific engineering objectives required by the situation in the city--that is:

(a) Effluents will most likely be used (illegally) for the irrigation of salad crops and vegetables eaten raw--therefore, a very high degree of removal of pathogenic micro-organisms must be achieved;

(b) Since effluents will be used for irrigation, maintenance of high levels of nutrients in the effluents is desirable;

(c) Urban development may in time reach areas near the sewage treatment plant sites, so that nuisance-free operational conditions must be assured.

The design criteria recommended by the consultants call for stabilization lagoons with an anaerobic first-stage pond followed by a series of three facultative and aerobic ponds for a total detention time of about 30 days. These general design criteria provide a sound basis for achieving the three design objectives stated above. Further chlorination should not normally be required for the effluents of such lagoons.

At certain sites recommended for treatment plants, land areas are limited and the consultants have recommended mechanically aerated lagoons which have much shorter detention periods than the non-aerated lagoons. The design recommended by the consultants for these aerated lagoons should achieve objectives (b) and (c), as stated above, but will not achieve objective (a), i.e., effective pathogen removal. If mechanically aerated lagoons are accepted as a solution at sites with limited land areas, it is recommended that the effluent be chlorinated in a system that assures effective mixing to ensure intimate and complete contact of the chlorine with all parts of the effluent stream, so as to ensure two hours of contact prior to application to crops. Pilot plant studies will be needed to determine the dosage of chlorine required to achieve effective inactivation of the enteric pathogenic micro-organisms. Experience in other areas suggests that chlorine doses of 10-20 mg/l may be required to achieve this vital objective. Such chlorination of the effluent would be required for most conventional sewage treatment systems.

In the early years of the project, land areas should be sufficient for the construction of stabilization lagoons with long detention periods, even at sites with limited land areas. As sewage flows increase with increasing population, these plants could be converted to aerated lagoons to prevent odour nuisances from developing. It is recommended that this procedure be followed in the early years of the project to avoid the high costs of chlorination and energy associated with aerated lagoons.

(iii) Staging of construction

Since the major social and economic benefits of the project will be derived from the supply of well-treated sewage effluent for agriculture, treated effluent could, as soon as possible, replace the use of raw sewage for irrigation of salad crops and vegetables eaten raw.

(c) Conclusions and recommendations for the city

(i) The irrigation with untreated sewage of some 20,000 tons per year of salad crops and vegetables eaten raw is undoubtedly a major source for the transport and spread of pathogenic enteric micro-organisms to the population of the city.

(ii) There is sufficient evidence, even if it is mainly circumstantial, indicating that sewage-irrigated vegetables are one of the main pathways for the dissemination of typhoid fever in the city. Other enteric diseases may also be transmitted by this same source.

(iii) A major portion of the typhoid fever cases and other enteric diseases are preventable mainly by reducing the exposure of vegetables to irrigation with raw sewage.

(iv) The most cost-effective and socially beneficial solution for the city is the introduction of a system of sewage treatment to remove the pathogens from the sewage and allow for its continued economically beneficial use in agriculture.

(v) Stabilization lagoons, as recommended by the GLO/80/004 consultants, are the most effective sewage treatment system for the city and would achieve the high level of pathogen removal required in a low-cost, robust system. The effluent would still contain valuable nutrients of economic value to agriculture.

(vi) The investment in sewerage and sewage treatment as proposed in the Master Plan is a highly beneficial investment which should provide good social and economic advantages.

(vii) Studies should be made to determine a programme of construction scheduling that will provide early benefits from sewage treatment.

(viii) The early construction of the pilot plants is vital to gain experience in plant operation and to generate data required for the final design of the treatment plants.

(vix) During the interim period, until the benefits of the sewage treatment can be fully achieved (about 10 years), other programmes to control typhoid fever and other enteric diseases transmitted by sewage irrigated vegetables should be carried out. These include the following:

- Restrictions on the type of salad crops grown in sewage-irrigated fields;
- Health education to promote washing and disinfection of all vegetables eaten raw;
- Selective typhoid vaccination programmes of highly susceptible groups;
- Identification and cure of typhoid carriers; and
- Inspection and control of food hygiene in public eating places.

The World Bank is considering supporting the implementation of the Master Plan and the associated measures to decrease the health risks to the population.

## 4. Waste-fed aquaculture (Resource Recovery Project activities in Lima, Peru)

### Introduction

The following paragraphs provide a brief introduction to the aquaculture studies conducted at the San Juan lagoons in Lima, Peru, during 1983 and 1984. This introductory information is primarily gleaned from project draft reports prepared by research scientists in Lima. The principle parties involved in the project are listed below:

CEPIS--Centro Panamericano de Ingeniería Sanitaria y Ciencias del Ambiente: water quality monitoring and sanitary engineering technical assistance to secure relatively steady-state water quality and quantity conditions within the ponds for aquaculture;

UNA--Universidad Nacional Agraria: fish culture and fish processing, as well as microbiology on processed fish;

USM/IVITA--Universidad Nacional Mayor de San Marcos, Centro de Investigación Instituto Veterinario de Investigaciones Tropicales y de Altura: bacteriology and parasitology on raw fish and prawns, as well as parasitology on pond sediment; and

ITINTEC--Instituto de Investigación Tecnológica Industrial y de Normas Técnicas: mesophilic batch digestion of animal manure and collaboration with UNA for special fish culture of tilapia in concrete tanks.

SERPAR--Servicio de Parques: provided overall coordination of the various research groups participating in the project. Also, SERPAR was responsible for operating and maintaining the lagoons in accord with water quality information obtained and technical assistance provided by CEPIS. Recently, overall management of the San Juan lagoons has been transferred to SEDAPAL, Servicio de Agua Potable y Alcantarillado de Lima. A national programme to encourage waste-water reuse and development of ecological green belts is under development in SENAPA, Servicio Nacional de Abastecimiento de Agua Potable y Alcantarillado.

The World Bank provided over-all conception and direction of the project, as part of the UNDP sponsored global research and development project on integrated resource recovery. The resident office of the UNDP in Lima helped to obtain the initial government approvals for research and thereafter facilitated the administration of research contracts. To assist the local research scientists, the World Bank arranged for the provision of intermittent technical assistance.

Midway through the project, financial assistance to support the continued project work of some of the local research was donated by the German Agency for Technical Cooperation (GTZ). This expert panel meeting is also being sponsored through donations from the GTZ.

(a) History of Developments

A special condition of Lima Metropolitana is that it does not rain. Often in the morning there is a mist, and for many months of the year it is cloudy. There is warmth and ultraviolet light enough for high levels of biological decomposition of waste water in lagoons throughout the year.

Aside from two small river basins cutting through Lima Metropolitana (e.g., Rio Rimac and Rio Chillon), Lima is desert land. Ground water is deep, fairly well contained by overlying impermeable soils, and has a regional flow from the mountains westerly to the Pacific Ocean.

The concept of full-scale reuse of treated waste water has been steadily developing in Lima, for over two decades--beginning in 1959 with a demonstration of how to treat Lima's waste water in stabilization lagoons to the National Congress of Sanitary Engineering.

In time, under the direction and supervision of SERPAR, 21 stabilization lagoons were developed at the San Juan site in southern Lima. Through the signing of Supreme Decree No. 105-67-DGS in 1967, SERPAR was authorized to create forest land by irrigating with treated effluent from the San Juan lagoons.

About 100 hectares of land (most of which was desert, and part of which was closed sanitary landfill) have been converted by SERPAR to forest. Pilot plots of various fruits (e.g., pineapples and papaya), vegetables (e.g., corn and platanos) and flowers (e.g., roses and hibiscus) also have been created on-site. Attracted by the water, farmers invaded adjacent lands and set up irrigation systems to use the partially treated waste water to grow livestock fodder and even vegetables.

Paralleling the movement toward waste-water reuse, there has been an increasing concern about air pollution and the desire for green-belts ("entornos ecológicos") of forest land to filter and increase the oxygen level in the air. Air pollution, when coupled with cold, damp climatic conditions during many months of the year, lowers human resistance to respiratory infections. A review of Peru Ministry of Health statistics shows that tuberculosis and other respiratory infections are among the ten leading causes of morbidity in Lima. As a step towards improving environmental quality, Legislative Decree No. 143 of 1981 created the "Programa de Protección Ambiental y Ecología Urbana" and therein constitutionally mandated the implementation of green-belts.

Research and development studies have been an integral part of SERPAR's efforts toward waste-water reuse. With local funding as well as external support from the International Development Research Centre (IDRC), Canada and the Pan-American Health Organization (PAHO), CEPIS has studied the mechanisms of treatment occurring in the lagoons and the levels of water quality achievable through various sequences of lagoons and periods of retention.

Since 1973, with the formation of a special multisectoral commission in Lima, San Bartolo (a 5,000 hectare site south of Lima Metropolitana) has been studied as a possible site for full-scale demonstration of waste-water reuse.

In 1980, a group from Israel established the pre-feasibility of irrigation with treated waste-water at San Bartolo. In 1981, UNA/CEPIS was engaged by SERPAR to further evaluate costs and benefits of the San Bartolo project. The concept was also studied from an engineering perspective, by Engineering Science, Inc. of the United States, as part of a master plan for water supply and sewerage for Lima Metropolitana. In 1983, funds were allocated for an in-depth study of costs and benefits and development of preliminary engineering designs, and a group of consultants is engaged in this study.

For reuse systems to be successful in the long term (especially in arid areas), accumulation of salts and metals in the roots' cross section should be limited. To accomplish this, waste-water treatment should strive for high removals of suspended solids and precipitation of dissolved solids. Also, longer retention times are needed to provide enhanced die-offs or removals of potentially pathogenic micro-organisms, and thereby minimize public health risks. The inclusion of aquaculture within the final stages of a treatment scenario could address these treatment needs. Also, revenues from the sale of the fish and/or plant byproduct could be used to offset the costs of obtaining a higher quality waste-water effluent and its appropriate disposal.

Over the past two years, with external support from the World Bank, UNDP and GTZ, aquaculture studies have been incorporated into the over-all scheme and into operation of the lagoons; lagoons having been resequenced to obtain higher levels of treatment, and both tilapia and prawns are being grown in these lagoons of higher water quality. These studies have been performed by local research teams at UNA, USM/IVITA, and CEPIS, under the co-ordination umbrella of SERPAR. As part of the aquaculture studies, pathogenic micro-organisms were being monitored in lagoon effluent and in harvested fish and prawns.

In co-operation with these studies, but with local industry financial support, ITINTEC has been performing studies on mesophilic anaerobic digestion of animal manure. Some of the slurry has been provided to UNA for use in aquaculture of tilapia in tanks supplied with potable ground water. Depending on the need for supplemental sources of fish food at San Juan lagoons, these studies could lead to including anaerobic digestors in the next round of research developments at San Juan.

(b) Summary of key aquaculture findings

Water Quality. Key indicators of water quality (e.g., dissolved oxygen and BOD) are regularly monitored in main sewage interceptors and rivers by the Ministry of Public Health. In addition, as part of the water supply and sewerage master planning effort, water quality of main interceptors was analyzed for a number of parameters, including heavy metals. The data clearly indicate that the over-all quality of waste water in the main interceptor of the south is markedly better than that of interceptors in the north, reflecting the limited extent of industrial development in the southern region of Lima Metropolitana.

Earlier studies by CEPIS at San Juan (lagoons located in the southern portion of Lima Metropolitana) to develop stabilization pond design relationships have shown a high correlation of removed BOD load versus applied

BOD load for the primary and secondary ponds of San Juan, a correlation between total BOD and suspended BOD, and a clear relationship between COD and BOD.

These earlier studies also showed the primary and secondary ponds to have limited nitrification potential. Furthermore, batch operation of "tertiary" ponds showed 0.5-1.6 mg/l $NH_3$-N while the continuous flow "tertiary" ponds averaged effluents of 14-16[3] mg/l $NH_3$-N. (The expressions "tertiary," and "fourth and fifth levels" are used to define the polishing lagoons after the secondary treatment and do not hint at any chemical or mechanical treatment.)

In one battery of ponds, there were four ponds in the sequence of treatment. In another battery of ponds, there were five ponds of treatment. Water depth in the fourth and fifth level ponds was lessened in order to avoid risk of stratification. Inflow to the series of third level ponds was reduced, with just enough provided from the second level ponds to compensate for evaporation and seepage loss, and the remainder discharged to the adjacent farmer's irrigation network.

During Phase II, there was an accidental upset of the operation in January 1984. At that time, gates were opened by adjacent farmers in order to let through large quantities of waste water to their irrigation channels. A shock load of secondary effluent entered the third level pond of the second battery, and thereafter flowed into the fourth and fifth level ponds. Dissolved oxygen (DO) levels were temporarily depressed, un-ionized ammonia levels peaked.

Dissolved oxygen is a controlling parameter in aquaculture. At San Juan the third, fourth and fifth level lagoons usually maintained DO levels at sufficiently high concentrations (averaging well above 2 ppm and often reaching 10-20 ppm in the afternoon) appropriate for aquaculture of fish and prawns. The typical morning depressions of oxygen had no noticeable effect on the growth and survival of the fish and prawns.

For fish culture (particularly when including shellfish), ammonia at excessive levels (specifically un-ionized ammonia) is toxic.1/ Toxicity is most severe when pH is high (as in late afternoon when pH rises to above 8.0 due to photosynthesis activities). Therefore, aquaculture was recommended not to take place in ponds exceeding a maximum allowable ammonia in the fish culture ponds of 1 - 1.5 ppm. For the most part, ammonia levels in the third, fourth and fifth level ponds were acceptable. When they peaked in Battery 2 after the accidental shock loading, however, significant mortalities of tilapia occurred and all of the prawns died.

Detergents are also toxic to fish, with the lethal level depending on the fish species. From experiments carried out in Israel, a combined concentration of alkyl-benzene-sulphonates (ABS) and soft long chain benzene sulphonates (LAS) was recommended not to exceed 1 - 1.25 ppm in the fish culture ponds. Detergent removal rates at the San Juan lagoons were found to be limited; but fortunately the detergent levels in the raw sewerage were low. The resulting concentrations in the fish culture ponds apparently did not harm the fish.

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1/ These conclusions are based on research works in Israel, Thailand and other countries.

Removal of faecal coliform was shown to clearly increase with retention time of waste water within the lagoons. Continuous flow in the third level ponds resulted in die-off of faecal coliform to levels below $10^4$/100 ml.

Salmonella exhibited similar die-off rates to faecal coliform. Antibiogram tests conducted on all types of isolated salmonella showed resistance to antibiotics. This presents some concern with respect to waste-water treatment and reuse, because resistant bacteria of one type can transfer their resistance to bacteria of other types through conjugation and bacteria resistant to antibiotics tend to also be resistant to other physical and chemical factors, e.g., chlorination. For this reason, the final stages of sediment quality analysis by CEPIS are including enterobacterioceae resistance to antibiotics.

Good removals of pathogenic protozoa and helminths are typically achieved by the completion of secondary level treatment at San Juan. Studies conducted by IVITA on the sediments from various ponds showed protozoa cysts and helminth eggs in the sediment of primary ponds.

Fish culture (including prawns). For Phase I of the aquaculture studies, the predominant objective was to assess and demonstrate survival and growth of fish and prawns. Nile tilapia fish were chosen for their reported resistance to high organic contents and low oxygen levels within the aquatic environment. Prawn were chosen for their potentially high market value in Peru and other countries, and giant prawn were specifically selected for comparatively tame and less cannibalistic behaviour, fast growth rate, short larval period and high tolerance to temperature changes relative to other types of prawns.

For Phase II of the aquaculture studies, the objectives were to further assess growth and to begin to assess optimum carrying capacity and stocking density of the ponds. While only monoculture had been done in Phase I, polyculture studies were started during Phase II. The common carp was selected to be cultured together with tilapia and prawns in the same pond, and again to further strengthen the demonstration effect of the studies.

The Phase I aquaculture began with importation of young prawns from Israel and Panama and the reproduction of locally available tilapia whose lineage traced from Israel. Once the juveniles were sufficiently grown to be added to the ponds, bioassays in mesh cages within the ponds were performed. Fish were held for one week in the cages to check survival potential. Ninety per cent of the tilapia and 75 per cent of the prawns survived the bioassays. Thereafter, tilapia were stocked in two fourth level ponds and one third level pond. As a reference point, tilapia were already being cultured in clear water ponds at Satipo. Prawns were stocked in the fifth level pond. Furthermore, prawns were placed in clear water ponds in Satipo, as well as in concrete tanks at the UNA campus.

For Phase II, common carp were imported from Panama. Because of a delay in importation, the Phase II monoculture studies on tilapia and prawn were begun first. Polyculture studies of carp, tilapia and prawns were begun about five months later.

Monthly samplings during both Phases I and II were conducted to measure weight and length of each species. At the end of the growth season, all fish were removed by use of a large net and measured. Because of the previous use of these ponds for waste-water treatment, some had a thick bottom blanket of sludge. While the sludge was not very problematic to the fish stocking and growing activities, during harvest significant turbidity occurred, oxygen contents plummetted and fish rose to the surface gulping for air. This condition was believed to have been the primary cause of mortality of prawn during Phase I. Undoubtedly, it is likely that significant ingestion of contaminants occurred during harvests, and that the microbiology results for skin and digestive tract were subsequently elevated.

Phase I took place during the winter season (June through October 1983), during which pond water temperatures averaged about 21°C in the morning. In January 1984 an accidental shock load to the third level (T2) pond occurred, and over a period of several weeks resulting dissolved oxygen and ammonia level changes led to significant mortalities. Only 39.8 per cent of the tilapia in the third level pond survived. About 87.7 per cent of the tilapia in the fifth level pond survived--comparable to survival measured during Phase I. It is conceivable that as the organic matter decomposed in the pond sequence, pH level dropped and offset the toxic effects of the un-ionized ammonia.

Polyculture in Battery 1 was unaffected by the accident in Battery 2. Monthly control samples indicate good growth, in fact tilapia have been growing much faster in polyculture.

Fish Processing. In Peru, there is a traditional market for salted fish. Prices of 16.00 Intis/kg are typically obtained in the market for salted fish, versus only 4.00 Intis/kg for raw fish.2/ Salted fish typically have a shelf life of 2-3 weeks, and even longer if refrigerated. If salted fish are subsequently dried, they can have a shelf life of one year.

After the harvests of Phase III, researchers at UNA processed tilapia by both the wet salting and smoking methods. Colour, texture and taste of both salted and smoked tilapia were considered good and competitive with other locally available products.

Microbiology. Bacteriology and parasitology studies on raw fish were performed by USM/IVITA. The bacteriology studies separately analyzed digestive tract content, peritoneal fluid and muscle. Meticulous laboratory procedures were followed in skinning and cleaning the fish, so that no contamination on the skin, fins, gills nor within the digestive system would get into the muscle samples.

The microbiology studies were done largely to assess whether micro-organisms which could be pathogenic to humans were contained within the fish. These same bacteria are not typically pathogenic to fish; however, they can stress the fish. In particular, invasion by any types of bacteria causes blocking of the immune system of the fish and therefore enhances the fish's vulnerability to infection by its own pathogens.

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2/ $US 1.00=Intis 10.97 (1985 period average)

Faecal coliform were not recovered from most tests done on muscle, and total coliforms were present in low concentrations. In earlier mocrobiology studies conducted in Israel, scientists had shown that coliform did not tend to reach fish muscle unless the concentrations of E. coli in water exceeded $10^6$. On the other hand, they had shown that other bacteria could be found in muscle when the E. coli concentrations were only $10^4$. The conclusions of the Israeli studies suggested that coliform may not be good indicator organisms for aquaculture studies. For this reason, Standard Plate Count (SPC) tests were performed within the latter stages of the Lima microbiological studies.

Based on SPC tests, a significant population of bacteria, including enteric bacteria, are present within the peritoneal fluid and muscle of raw tilapia samples from both third and fifth level ponds. E. coli, Citrobacter freundii, Klebsiella sp., Proteus vulgaris, and Enterobacter cloacae were found in fish from all the aquaculture ponds. Salmonella bacteria were isolated from some of the third and fifth level ponds.

All samplings of gill, muscle and digestive tract content of raw tilapia, carp and prawns were negative for protozoa cysts and helminths. These parasites were found present in the sediments of the primary pond. In general, parasites are believed to be removed by settling from the water column early in the treatment pond sequence. However, it warrants mention that amoeba cysts were found within the sediment of the fifth level pond.

A few trials of depuration were conducted, whereby fish were placed for three to seven days in clean water. Data from the subsequent microbiological studies are inconclusive. They did not show any decrease in bacterial content of the fish after depuration, and some cases indicated an increase.

Bacteriology studies on processed fish were performed by UNA. During processing, the tilapia were washed and fileted by standard commercial/home procedures. As a result, the knife used to cut open the fish and clean it was also used to do the fileting, and no antiseptics were used for disinfection. Any contamination on the skin and within the digestive tract of the fish could therefore be transferred to the muscle of the fish. Nevertheless, the bacteriology tests on salted and smoked tilapia indicated a reduction in over-all bacteria levels and total coliforms apparently attributable to processing.

By UNA and ITINTEC, tilapia were grown in clean water wherein digested animal manure had been used for production of fish food. USM/IVITA conducted microbiological studies on a sampling of the partially grown fish.

(c) Preliminary proposals for Phase III

In the next phase of work, emphasis would be on development of optimum fish culture operational conditions. A new fish culture pond and ground-water well would be constructed, so that water quality could be controlled by aeration and occasional additions of fresh well water. The fish culture pond would be somewhat removed from the waste-water treatment lagoons to ease public acceptance of the fish. It would also be outside of the general flow network of the lagoons, in order to curtail the potential for shock loadings and minimize acceptance problems with adjacent farmers who use treated waste-water effluent for irrigation. Special pond design features would be implemented to facilitate harvesting and sludge removal operations.

Experiments would be accomplished to determine the optimum stocking density and carrying capacity of the ponds. Monoculture and polyculture would continue to be compared. The need for supplemental carbohydrate food would be studied, and consideration given to the use of digested animal manure for generation of supplemental protein food.

More in-depth study of microbiology would be included, with some inclusion of virology studies and more in-depth classification of bacteria.

## E. Health aspects of waste-water reuse for irrigation of crops

by Fred M. Reiff*

### Introduction

Today, many developing countries, particularly the arid countries, are reusing sewage for irrigation as a means of compensating for water shortage problems. This has been practised for many centuries in many countries. Some countries do not admit to the reuse of sewage for irrigation, but they have so badly contaminated their rivers with raw sewage that they also are in effect irrigating with sewage. It is possible to reuse adequately treated sewage for controlled irrigation of select crops without adverse health affects, but it is also possible that the benefits obtained from irrigation with waste water can be offset by the adverse health effects associated with inadequate public health controls. It is expected that the combination of economic, demographic and weather conditions will encourage an increase in future reuse of waste water for agricultural and aquacultural purposes. The populations in dire need of irrigation water will not wait until all the epidemiological questions are answered regarding actual rather than potential risks and, for this reason, health officials and sanitary engineers will find it necessary to develop pragmatic, cost effective reuse projects which will not only be sufficiently safe but will yield information and experience for further improvement.

### 1. Health Risks

Municipal sewage contains two broad categories of agents which can have adverse effects on human health: pathogenic micro-organisms from faecal and urinary waste of humans and animals; and toxic substances generated and discarded by mankind. Figure 29 depicts the major human health concerns which stem from each of the agents.

For an adverse health effect to result from the application of sewage to land for agricultural purposes, exposure to the disease-producing agents must take place and the exposure must be of sufficient magnitude and duration to induce the effect. This is different for each of the agents. Table 38 lists the epidemiological and immunological features of the biological types of excreted pathogen.

The three most probable routes of exposure are: direct exposure of workers and nearby residents during transportation or application of the sewage or contact with sewage amended soil; consumption of the plants grown in the soil, or of animals feeding on these plants; and ingestion or contact with surface or ground water contaminated respectively by run-off or percolation. Risk assessment may be approached basically through two methodologies: epidemiological investigation and modelling. The major limitations of epidemiological investigations occur in control or accounting for the variables or in the identification of significantly large known exposed and

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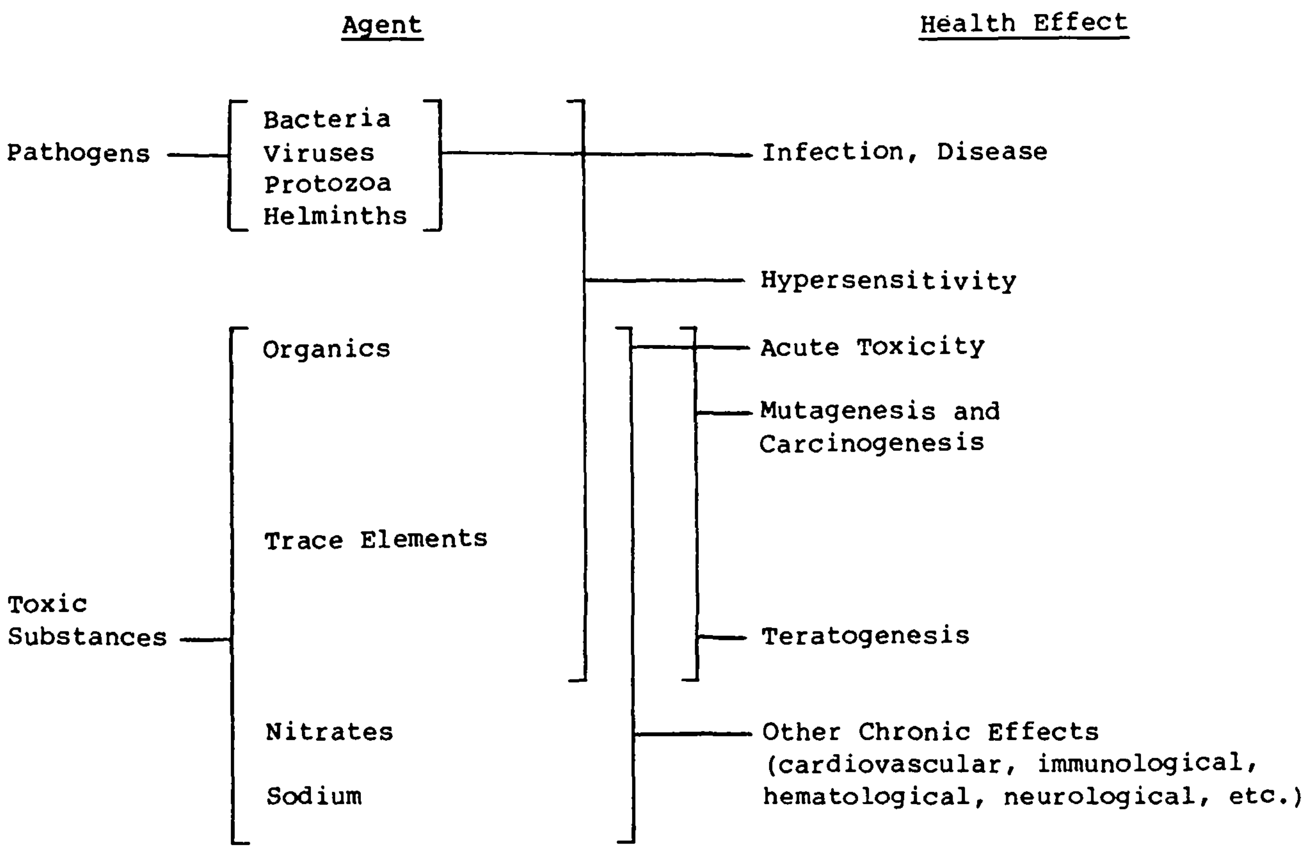


Figure 29. Human health concerns from pathogens and toxic substances

Source: Elmer W. Akin, Public Health Risk and Risk Assessment in Relation to the Management of Municipal Wastes on Lands, paper presented at PAHO Workshop on the International Transportation and Utilization or Disposal of Sewage Sludge.

unexposed groups with adequate health records and yet with other factors being equal. Time as well as intensity of exposure is also important for chronic, non-contagious diseases. The limitations of modelling are basically due to lack of information regarding occurrence, transportation, and fate of each agent, dose requirements and human exposure levels, as well as the combined effect of complex mixtures of varying concentrations of agents.

There are numerous determinants of actual health risk associated with reuse which are interrelated in a complex, but site-specific manner. Even though research is proceeding to remove some of the limitations, data and information gaps continue to exist for both approaches and tend to constrain scientifically-based risk assessments relative to waste-water reuse. This has resulted in the inclusion of relatively large safety factors in waste-water quality standards for irrigation. More recently, there has been a trend toward advocating an epidemiological approach in which decisions are based on actual health risks rather than potential health risks for irrigation with sewage in developing countries (Gunnerson, Shuval and Arlosoroff, 1984).

Table 38. Epidemiological and immunological features of the biological types of excreted pathogen

| Biological Class | Transmission | Infectous Dose | Does Infection Confer Long Lasting Immunity? |
|---|---|---|---|
| Viruses | Faecal-oral | Low | Yes |
| Bacteria | Faecal-oral | High | No a/ |
| Protozoa | Faecal-oral | Low | No |
| Nematodes | Development in soil | Low | No |
| Trematodes | Development in aquatic host | Low | No |
| Cestodes | Development in pig or cow | Low | No |

Source: R. G. Feachem and D. Blum, Health Aspects of Agricultural and Aqua Cultural Reuse of Wastewater in Developing Countries, London School of Hygiene and Tropical Medicine, Department of Tropical Hygiene (London, October 1984).

Note:

The properties listed do not apply to viruses, bacteria, etc., in general, but only to those excreted pathogens.

a/ Except in the case of typhoid fever.

(a) Viruses

The viruses which should be considered in the design of waste-water reuse projects are Poliovirus, Hepatitis A virus, and Rotavirus, which respectively are the infectious agents of poliomyelitis, infectious hepatitis, and diarrhoea (Feachem and Blum, 1984). These viruses utilize the faecal-oral transmission route and have a low infectious dose. Poliomyelitis is an extremely acute disease which causes severe crippling and death. Vaccines are available for immunization against polio, but not hepatitis and rotavirus infection. Hepatitis A infection confers long-lasting immunity as does rotavirus. Rotavirus is associated with severe infant/childhood diarrhoea contributing to the high morbidity and mortality of children. Hepatitis A is a mild disease for children, but an acute disease for adults with the severity generally increasing with age. The lack of isolation techniques for Hepatitis A virus and the lack of adequate detection techniques of rotavirus has prevented any direct studies on their inactivation in sewage treatment processes. Indirect studies have shown Hepatitis A to be extremely resistant to chlorination, and rotavirus to be less subject to inactivation than poliovirus. Although the mechanism of removal in stabilization ponds is not well understood, it appears that at least a 4 log reduction can be obtained in 30 days at temperatures of 25°C or more.

(b) Bacteria

The pathogenic bacteria which are of significance in sewage irrigation projects are Campylobacter jejuni, Escherichia coli, Salmonella spp., Shigella spp., and Vibrio Cholerae. Cholera, typhoid, bacillary dysentery and other bacillary enteric infections, which can be transmitted by sewage irrigation projects all can have multiple pathways of transmission including food, water, and direct contact. Only typhoid imparts lasting immunity; recurring infection occurs with the others. For all of these diseases, the greatest risk occurs when crops irrigated with sewage from areas where any of these diseases are endemic are sold in areas where the diseases are not endemic.

(c) Helminths

Many species of parasitic helminths may infect mankind and the ova of all but Schistosoma Haematobium are passed in the excreta. The helminths of significance in irrigation with sewage are the Ancylostoma duodenale and Necator americanus, Ascaris lumbricoides, Trichuris trichiura and Taenia saginata.

(i) Ancylostomiasis (or hookworm) is important because it can infect the health workers. This is a chronic debilitating disease, often referred to as the disease of laziness. It can cause anemia, protein loss, and malnutrition. It may be associated with mental retardation in children. Man is the reservoir for human hookworm. Eggs are discharged by the female located in the small intestine of a host and they begin development in the intestine before being evacuated in the faeces. If the faeces is deposited in a suitable environment, the eggs hatch within 48 hours and the larvae begin development, undergoing transformation in 4 or 5 days to the filariform larvae which is infective to man. The larvae survive in moist warm soil from 3 to 15 weeks. Infection of man occurs when the filariform larvae penetrate the skin of the feet or ankles (or by oral ingestion of A. duodenale). The larva migrates to the heart and then the lungs where it ascends the bronchi and trachae, is swallowed and reaches the small intestine to which it attaches, all within 24 to 48 hours after penetration of the skin. It undergoes two further moults and begins laying eggs 4 to 8 weeks after infection.

(ii) Ascariasis (roundworm) is a helminthic infection of the small intestine. Symptoms are variable, mild, vague or absent usually depending on the parasite burden, but include coughing, fever, and pronounced blood eosinophilia, abdominal pain, vomiting, and bowel obstruction. It can be fatal. Its mode of transmission is by ingestion of eggs from soil contaminated with human faeces. The eggs must undergo about three weeks of embryonation in soil at warm temperature to become infective. Soil-contaminated vegetables eaten uncooked are probably the most common vehicle. A single infectious egg can induce infection. Ingested embryonated eggs hatch in the intestinal luman, the larvae penetrate the gut wall, and migrate to the liver and lungs where they develop. After 9 or 10 days, they pass through the air passages, ascend the bronchi, are swallowed and reach the small intestine, where they grow to maturity about 2 months after ingestion. Then they mate, the female discharges eggs, the cycle can be repeated. The adult female grows up to 40 cm in length and the male 30 cm. The adult female may lay up to 200,000 eggs per day.

(iii) Trichuriasis (whipworm) is a helminthic infection of the large intestine. Light infections are often asymptomatic, heavy infections result in diarrhoea, bloody stools and rectal prolapse. The transmission is by ingestion of embryonated eggs. Eggs passed in the faeces of an infected person need about three weeks in suitable soil conditions for embryonation. Once ingested, the embryonated eggs hatch and attach to the large intestine and develop into the adult worm. About 90 days after ingestion, the females begin to discharge eggs. Adults reach a length of about three to five cm and the female will lay 2,000 to 10,000 eggs per day. One infectious egg can induce infection.

(iv) Taenia saginata infection (beef tapeworm) is an intestinal infection which includes the symptoms of nervousness, insomnia, weight loss, anorexia, abdominal pain and the annoyance of having segments of the worm emerge from the anus. It is a non-fatal disease. The mode of transmission is by ova passed in the faeces of man being ingested by cattle. The ova are infectious only to cattle in which the larvae form develops in the flesh of the animal into the "cysticercus bovis" which is infective to man following his ingestion of raw or inadequately cooked beef containing the cysticerci. The incubation period in man is from 8 to 14 weeks. The adult can reach a length of 15 metres, but is usually between 6 and 10 metres long.

(d) Protozoa

Of the numerous protozoa which may be present in waste water, the three species of major health significance to humans are Entamoeba histolytica, Giardia lamblia, and Balantidium coli. The Entamoeba histolytica causes an acute enteritis known as amoebic dysentery. Giardia lamblia causes an infection of the small intestine associated with malabsorption of fats, steatorrhea, bloating, abdominal cramps and weight loss. Balantidium coli causes a disease of the colon characterized by diarrhoea. It is not uncommon to encounter asymptomatic carriers in all three of these diseases and they are the people primarily responsible for transmission. Since these protozoa and their cysts are highly sensitive to drying, and are destroyed rather rapidly at temperatures above 40°C, as well as by ultraviolet light, their survival on plant surfaces is expected to be rather brief, but a number of epidemiological reports have linked the transmission of amoebiasis to vegetables irrigated with raw sewage. The survival of cysts for sufficient periods to infect humans under poor management conditions is confirmed by the recent isolation of *E. histolytica* and *Giardia lamblia* on waste-water irrigated fruits and vegetables in Mexico City (Akin). Because of the large size of the organisms and cysts, it is unlikely they would find their way into ground water except under extremely unusual soil conditions.

(e) Chronic non-contagious diseases

Municipal sewage contains proteins and other nitrogenous organics, as well as urea and a number of their breakdown products. Fortunately, bacteria in the soil rapidly decompose most forms of organic nitrogen to ammonium, and the aerobic conditions of most soils allow nitrosomonas and nitrobacteria to oxidize ammonium to nitrate and nitrate to nitrite. From a human health standpoint, inorganic nitrogen is a concern for infants, less than 3 or 4 months of age, in that high nitrate levels (greater than 10 mg/l) in drinking water can cause methemoglobinemia.

Toxic organics present a rather new problem in irrigation with sewage. Only a very small percentage of the organic contents of sewage are substances that would be acutely toxic to humans. The concern is primarily for the potential for causing chronic disease resulting from long-term low dose exposure from all sources. Although the major contributor of toxic organics to municipal sewage is usually assumed to be industry, consumer products, such as household cleaners, solvents, pesticides, laundry products, paint products, polishes, preservatives, and cosmetics also play a growing role. Although much research has been conducted on insecticides, fungicides, and herbicides, insufficient information is available to assess food chain risks of waste-borne toxic organics. The fate of toxic organic substances in sewage stabilization lagoons merits additional research, since some of the reuse projects concern sewage flows from large industrial cities.

Generally, cadmium, lead and mercury are considered to be the trace elements of greatest health concern, and their health effects are well understood. The major fear is of the exposure to humans resulting from the consumption of plants that have taken up cadmium through the root system. Of these three metals, cadmium has the greatest potential to cause a health problem in irrigation with sewage, particularly when the sewage is from an industrial city. Ingested cadmium accumulates in both the kidneys and liver and displaces zinc in various enzymes and may cause serious damage. In extremely high concentrations, it can cause the bones to become so brittle and weak that the ribs can be fractured by a coughing spell (Itai itae disease in Japan). It has also been suspected of being one cause of hypertension. Lead and mercury can cause severe neurological damage and other serious health effects.

The uptake of heavy metals from soils by plants is a very complicated process, but in general is reasonably well understood, with more than 200 excellent scientific papers written on this subject. The relationship between soil properties such as pH, ion exchange capacity, and mineralogy, to the build-up of heavy metals in the soil due to application of sewage and sewage products has been thoroughly studied. Guidelines for permissible application rates should be transferable to developing countries.

In porous soils with low pH and low cation exchange capacity, irrigation with sewage high in cadmium could conceivably result in elevated levels of cadmium in the ground water, and these factors should be taken into consideration when sewage from industrialized cities is being considered for irrigation or recharge.

(e) Risk reduction

Reduction of elimination of health risks related to excreta and sewage disposal can be based on attacking various links in the chain of events which occur in the transmission of the disease. The strategies which are used in carrying this out are isolation, detention, dilution, removal and destruction of the pathogens as well as immunization of the target population. These strategies are used alone or in various combinations in methodologies to reduce the health risks associated with irrigation of crops with reclaimed sewage. Most of the methodologies, at least to some extent, take advantage of the recognized fact that conditions outside the human body are usually unfavourable to the survival of pathogens, because of competition and predation by other organisms, as well as the adverse factors of dessication, unfavourable temperatures, and pH, ultraviolet radiation, and the like. This causes a die-off in all but a few pathogens which have demonstrated a capability to multiply under certain environmental conditions. The rate of die-off depends on many factors, but primarily competition, temperature, predation and pH. Tables 39, 40 and 41 indicate ranges of survival times under various circumstances.

Table 39. Survival of organisms in faeces and nightsoil

| Type of organism | Usually less than: | Maximum |
|---|---|---|
| Enteric viruses | 3 months | 5 months |
| Indicator bacteria | 4 months | 5 months |
| Salmonellae, shigellae | 1 month | 5 months |
| Vibrios | 5 days | - |
| Tubercle bacilli | 5 months | 2 years |
| Protozoan cysts | 10 days | 1 month |
| Helminth ova: | | |
| Ascaris | Many months | |
| Others | Highly variable | |

Source: R.G. Feachem and others, Water, Health and Development: An Interdisciplinary Evaluation (London, Tri-Med Books, 1978).

Table 40. Survival of pathogens in soil

| Type of Organism | Usually less than: | Maximum |
|---|---|---|
| Viruses | 3 months | 6 months |
| Bacteria | 2 months | less than 1 yr |
| Protozoa | 2 days | 10 days |
| Helminth ova | 2 years | 7 years |

Source: R.G. Feachem and others, *ibid*.

Table 41. Survival of pathogens on crops

| Type of Organism | Usually less than | Maximum |
|---|---|---|
| Enteric viruses | 1 month | 2 months |
| Indicator bacteria | 1 month | Several months |
| Salmonellae | 1 month | 6 months |
| Vibrios | 7 days | - |
| Cysts | 2 days | 5 days |
| Helminth ova | 1 month | 5 months |

Source: R.G. Feachem and others, *ibid*.

## 2. Methodologies for Risk Reduction

### (a) Medical interventions

Immunization of the targeted population is probably the least effective means of reducing the risks to affected populations, primarily because there are no immunizations against the helminthic and protozoan diseases associated with sewage, and immunization against the bacteriological diseases, except for typhoid, are generally rather short-term or non-existent. Although prophylaxis and chemotherapy are effective as a component of a programme to obtain an initial reduction in helminthic infections, to be followed by other preventive measures, it is not an accepted public health practice to carry them out on a recurring basis for a population which continues to be reinfected.

### (b) Prohibition and restriction of crops

Some countries prohibit the agricultural use of sewage altogether, but this is not a realistic solution for arid developing countries. They will almost surely continue to irrigate with sewage. Restriction of certain crops is presently being practised in some countries, with mixed success. Some crops are less likely than others to be implicated in the transmission of sewage-borne diseases. Non-food fibre crops, such as cotton and flax are examples of crops with a low health risk, whereas lettuce and strawberries are examples of high risk crops when sewage is used for irrigation. In technically-advanced countries, restrictions of irrigation to low-risk crops have been quite effective in reducing infection from irrigation with sewage, especially when coupled with regulations governing irrigation techniques, but effective surveillance and enforcement are required. Developing countries often lack this capability and sporadic outbreaks of diseases due to non-compliance with restrictions do occur.

### (c) Restriction of irrigation methods

It is possible to reduce the risk of contamination of crops with sewage by selecting methods of irrigation which minimize direct contact between waste water and crops. Unfortunately, the safer methods, such as subsoil and drip irrigation have the greatest capital cost. Furrow irrigation and flood irrigation are the least costly, but present a greater risk for direct contamination of the crops, as well as greater risks to the farm workers. Spray irrigation completely exposes the crops to the irrigation water and should not be utilized for crops intended for human consumption when sewage is used for irrigation.

Some countries have restrictions that irrigation with sewage be stopped one month before harvesting for all crops intended for human consumption. Compliance is difficult to obtain and verify.

### (d) Improved worker hygiene

Since one of the high risk groups is the agricultural workers, various interventions to protect them are possible to implement. This could entail changes in customs and habits, as well as protective footwear and clothing. Little information is available on actual interventions and their effectiveness.

(e) Disinfection and cleaning of crops

The cleaning and/or disinfection of potentially contaminated crops in the market or home are potentially effective, but difficult to implement. Cleaning in the market place usually reverts to cleaning for appearance rather than pathogen removal. At least one study showed vegetables to become more contaminated from "cleaning" with contaminated water as they went through the marketing process. Cleaning or disinfecting in the home necessitates facilities which are frequently non-existent in the homes in developing countries.

(f) Improved sewage treatment

Many of the existing sewage reuse schemes utilize raw sewage for irrigation, usually presenting a health hazard. Many countries discharge raw sewage directly into rivers and other bodies of water which are also used as a source of irrigation water. Where dilution and die-off of pathogens are sufficiently high, there will be a low health risk asociated with this practice. However, increasing pollution of rivers in some developing countries has exceeded the self-purification capacity of the rivers, converting them essentially into open sewers, and irrigation with those waters presents the same health risks as it does with raw sewage. Sewage treatment in developed countries is carried out primarily to protect the environment through reduction in biochemical oxygen demand, suspended solids, and nutrients. These methods of treatment are not the most effective or efficient for pathogen removal.

Ideally, sewage effluents used for irrigation should be treated to remove or kill all enteric pathogens all of the time. This means that the responsible institutions and agencies must be able to not only afford the cost of the level of treatment required, but must also have adequate manpower skills and infrastructure development to carry out and monitor the operations on a dependable basis. This is neither economically feasible nor practical in most developing countries. For this reason, it is necessary to concentrate on treatment processes which remove the priority pathogens, namely helminths and protozoa, and reduce the pathogenic bacteria to a level which will not induce disease.

There is considerable literature concerning the fate of pathogens in various sewage treatment works except for rotavirus, Hepatitis A virus and Campylobacter jejuni. Tables 42, 43 and 44 respectively indicate the removal efficiencies of bacteria, viruses and cysts and ova in various methods of sewage treatment. Conventional sewage treatment and septic tanks have the lowest removal rates. Advanced waste treatment with tertiary treatment processes, including disinfection, can eliminate all pathogens from the effluent, but these technologies are far too costly and complicated for developing countries to install and maintain. It is interesting to note that many of the advanced waste treatment processes incorporate a tertiary lagoon.

Table 42. Removal of bacteria in waste-water treatment

| Processes | Percentage Removal<br>E. coli | | | |
|---|---|---|---|---|
| | E. coli | Salmonella | Shigella | Cholera vibrio |
| Primary settling | 50-90 | 50-90 | 50-90 | 50-90 |
| Trickling filter plant<br>Primary settling<br>Trickling filter<br>Secondary settling<br>Sludge digestion<br>Sludge drying | 90-95 | 90-95 | 90-95 | 90-95 |
| Activated sludge plant<br>Primary settling<br>Aeration<br>Final settling<br>Sludge digestion<br>Sludge drying | 90-99 | 90-99 | 90-99 | 90-99 |
| Oxidation ditch, settling, sludge drying | 90-99 | 90-99 | 90-99 | 90-99 |
| Stabilization ponds<br>3 cells<br>25 days detention | 99.99-99.99999 | 90.99-100 | 99.99-100 | 100 |
| Septic tank | 50-90 | 50-90 | 50-90 | 50-90 |
| Tertiary lagoons | 99-99.9999 | 99-100 | 99-100 | 99-100 |
| Land application or slow sand filters | 99.99-100 | 100 | 100 | 100 |
| Chlorination | less than 100 | 100 | 100 | 100 |

Source: Feachem and others (1978)

Table 43. Removal of viruses in waste-water treatment

| Processes | Concentration of viruses: Influent No/Litre | Concentration of viruses: Effluent No/Litre | Percentage Removal |
|---|---|---|---|
| Primary settling | $10^3$-$10^5$ | $10^3$-$10^5$ | 0-30 |
| Trickling filter plant<br>Primary settling<br>Trickling filter<br>Secondary settling<br>Sludge digestion<br>Sludge drying | $10^3$-$10^5$ | $10^2$-$10^4$ | 90-95 |
| Activated sludge plant<br>Primary settling<br>Aeration<br>Final settling<br>Sludge digestion<br>Sludge drying | $10^3$-$10^5$ | 10-$10^4$ | 90-99 |
| Oxidation ditch, settling, sludge drying | $10^3$-$10^5$ | 10-$10^4$ | 90-99 |
| Stabilization ponds<br>3 cells<br>25 days detention | $10^3$-$10^5$ | 0-10 | 99.99-100 |
| Septic tank | 0-$10^9$ | 0-$10^8$ | 50 |
| Tertiary lagoons | 10-$10^4$ | 0-$10^2$ | 99-100 |
| Land application or slow Sand filters | 10-$10^4$ | 0-$10^2$ | 99-100 |
| Chlorination | - | - | Uncertain |

Source: Feachem and others (1978)

Table 44. Removal of cysts and ova in waste-water treatment

| | Percentage Removal | | | | |
|---|---|---|---|---|---|
| | Entamoeba Histolytica | Hookworm Ova | Ascaris Ova | Schisto-somes Ova | Taenia Ova |
| Primary settling | 10-50 | 50 | 30-50 | 80 | 50-90 |
| Trickling filter plant<br>Primary settling<br>Trickling filter<br>Secondary settling<br>Sludge digestion<br>Sludge drying | 50? | 50-90 | 70-100 | 50-99 | 50-95 |
| Activated sludge plant<br>Primary settling<br>Aeration<br>Final settling<br>Sludge digestion<br>Sludge drying | 50? | 50-90 | 70-100 | 50-99 | 50-95 |
| Oxidation ditch, settling, sludge drying | 50? | 50-90 | 70-100 | 50-99 | 50? |
| Stabilization ponds<br>3 cells<br>25 days detention | 100 | 100 | 100 | 100 | 100 |
| Septic tank | 0 | 50-90 | 50-90 | 50-90 | 50-90 |
| Tertiary lagoons | 100 | 100 | 100 | 100 | 100 |
| Land application or slow sand filters | 100 | 100 | 100 | 100 | 100 |
| Chlorination | 100? | 0 | 0 | 100? | 0 |

Source: Feachem and others (1978)

Disinfection of treated sewage effluent in developing countries prior to reuse for irrigation should be viewed with skepticism. First of all, most of the developing countries are currently unable even to chlorinate their water supplies on a dependable continuous basis, and water supplies require far lower chemical dosage than does chlorination of sewage effluent. Since it is estimated that more than one half of the chlorinators on water systems are inoperative in developing countries, it is not realistic to expect them to function or be maintained any better on sewage treatment facilities. Additionally, the possibility of the production of chloro-organic compounds and possible harmful effect on the consumers of the crops would probably assure discontinuation of this expensive process.

It should be noted that these tables indicate that 3-cell 25-day detention stabilization ponds remove more than 99.99 per cent of each of the pathogens (bacteria, viruses, cysts and ova) listed. Although not all studies are in exact agreement with the percentages of pathogens removed (Bartone, 1984), almost all agree that stabilization ponds are the most efficient means of removing pathogens from sewage when they are well designed and well operated, with particular attention to the prevention of short circuiting and resuspension of settled pathogens.

## Conclusions

Because so many of the developing countries which are deficient in water resources are already using sewage for crop irrigation and because more reuse is planned for the future, it is important that any adverse health effects be minimized. Based both on studies and experience, and credible quantifiable health effects, there is a need for some form of sewage treatment preceding reuse. Economic, social and institutional conditions in these countreies necessitate a risk-benefit approach in the selection of the method of sewage treatment. In order to balance this with capital and operating costs, prioritization of the pathogenic agents to be removed is necessary. The helminths which cause ascariasis, trichuriasis, taeniasis, and ancylostomiasis are of highest priority. The protozoa which cause amoebiasis and guiardiasis and the bacteria which are the infectious agents of typhoid, cholera, and gastroenteritis and diarrhoeal diseases follow closely and the viruses causing polio, infectious hepatitis, and rotavirus diarrhoea should also be removed.

All of this is possible by treatment in properly designed and operated sewage stabilization ponds. This is not only the preferred method of treatment for removal, but is also usually the least costly, easiest to operate and maintain, the most energy efficient, and the most reliable treatment in developing countries. Detention in stabilization ponds will also reduce the level of many toxic organics and heavy metals, even though the mechanisms are not well understood. Additional research could be valuable to further improve this method of treatment, but there is already sufficient knowledge to install reliable cost effective facilities, which will minimize the adverse health effects of irrigation with treated reclaimed waste water.

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# V. WEATHER MODIFICATION

## A. Cloud seeding - A source of water?

by L. Randall Koenig*

### 1. Introduction

The quantity of precipitation reaching the ground seldom equals the quantity of water in the cloud above. That is, clouds produce precipitation inefficiently.

At the middle of this century it was believed that essentially each raindrop originated as an ice particle. Since observations within clouds at sub-freezing temperatures often revealed large concentrations of small, supercooled water droplets, but few ice particles, the conclusion was reached that the inefficiency of clouds was due to less than optimal concentrations of ice particles. It followed that if, somehow, one could increase the concentration of ice particles, one could increase precipitation. Thus, the birth of the scientific period of weather modification occurred in 1946, with the discovery of the ability of less than one gram of dry ice to produce billions of ice particles in supercooled clouds.

Many of the early pioneers in this field believed that cloud seeding could be developed rapidly into a technology to solve many water shortage problems. However, the development of the science of weather modification has been much slower than anticipated, and history records cycles of optimism and pessimism. The cycles, in part, are due to the political context in which the work is often carried out and the response of decision-makers to the conflict between practioners and scientists.

Weather modification has developed along two lines, experimental research programmes and operational programmes. Projects seldom deal with both aspects but in recent years a few combined programmes have been undertaken. For the research projects the laboratory is the atmosphere but, unlike the laboratory, surrounded by walls, conditions of experimentation are not controllable and the repetition of experiments to check hypotheses or verify results is difficult. Observations at one site may or may not be applicable to another site and therefore the extent to which technology can be transferred generally is not clear. Research-oriented weather modification projects typically require many years of relatively costly field studies. Procuring commitments for this long-term work has proven to be difficult. Too often projects are started and then funding ceases before sufficient data are accumulated to produce definitive results. These factors, some related to the science, others to the economics and politics of doing science, result in slow progress.

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Progress is being made, however. The following will provide information on the current status of precipitation enhancement and its role as a possible source for water in developing countries.

## 2. Advantages and disadvantages

Cloud seeding operations require little infrastructure; therein lies a major advantage over most other means of acquiring more water. The technology is not well developed and at this time should be considered unreliable; therein lies its major disadvantage. To expand:

(a) Advantages

(i) Flexibility

- In principle, an operation can be moved from one location to another in response to demands;
- Operations can easily be stopped during periods when not needed;
- Operations can rapidly be put in place (but not with great efficiency).

(ii) Reversibility

- Little infrastructure needed. Therefore, essentially no physical "artifacts" remain if the programme is cancelled;
- No long-term effect on weather.

(iii) Cost effectiveness (perhaps).

(iv) Environmentally benign?

(v) Relatively few specialists required to run operations.

(vi) Often politically attractive.

(b) Disadvantages

(i) Technology not fully developed

- A project at a particular site would initially require research and development activities;
- Prediction of results is extremely difficult.

(ii) Difficulties in assessing results

- Costs of an assessment are similar to total costs of other aspects of the programme;
- Long period of time (five or more years) generally needed to gather data required for a scientifically-accepted evaluation.

(iii) Weather dependency

- The effect that can be produced depends upon what nature provides as raw materials;

- Since weather varies (day to day, year to year, etc.), the amount of water that can be produced will not be constant.

(iv) Potential socio-political problems (real and imaginary causes)

- One industry may favour more precipitation, another less;
- One group (political division, etc.) may accuse another of stealing its natural supply of precipitation;
- Perceived environmental problems;
- Blame for natural disasters (floods).

(v) Expertise necessary is not available in many developing countries; adequate training requires several years.

It should be made clear that there are few precipitation enhancement projects that have shown, to the satisfaction of the scientific community, the ability to increase areal precipitation. The modification of individual clouds has been repeatedly shown, but translating this to an economically attractive areal increase in precipitation has proven to be difficult.

## 3. Uses of cloud seeding to increase precipitation

In considering cloud seeding as a means of increasing water supplies, one should note the prevailing opinion is that the potential quantity of additional precipitation that can be artificially produced is roughly proportional to the amount that nature itself produces. If true, this indicates that cloud seeding will not be effective in smoothing seasonal rainfall. In section 4 the result of a cloud survey is shown that illustrates this point.

Routine use. Since weather modification has the potential of increasing water supplies in normal as well as abnormal years, it might be considered as a means to enhance the value of conventional water resource management tools such as reservoirs or to recharge underground aquifers. In fact, the routine, long-term use of precipitation modification to increase annual average precipitation is viewed by many advocates as the most practical use of precipitation enhancement and there are operations throughout the world, both in developed and developing countries, in which this is the goal of cloud seeding projects. Typically these projects are of long duration but they seldom have been designed with adequate provisions for evaluation.

Drought relief. Drought often brings demands for action. Not uncommonly this becomes translated into an emergency cloud seeding project. Drought relief projects are too often put in place in a political context. They are intended as emergency, short duration projects and all too often there is no provision made to gather data necessary for a proper physical and economic evaluation of the results. Consequently, very little information on their efficacy is produced. Since five or more years typically are required to obtain sufficient data for a useful evaluation, there is little prospect for proper evaluation of short-term drought relief projects.

The effectiveness of short-term drought relief projects invariably is quite controversial. A time series analysis of precipitation is inadequate. Droughts sooner or later are broken by nature. Just because precipitation increases after an operation starts should not be taken as a testament that the operation has been successful (similarly, if precipitation does not increase after the start of an operation, it would be a mistake to ignore the possibility that there would have been even less precipitation had the project not been put in place).

Certainly if nature does not produce conditions (for example, clouds) that can be modified to produce more precipitation, then man has no ability to increase precipitation. Unfortunately, there are too few data, especially from developing countries that experience chronic drought problems, to make useful assessments on the value of cloud seeding as a tool for drought relief, or for that matter, a routine water management tool.

Worldwide activity. Figure 30 contains information on worldwide precipitation enhancement activities based on data contained in annual issues of the Register of National Weather Modification Projects, a publication maintained by WMO and based on responses to a questionnaire sent to all members.

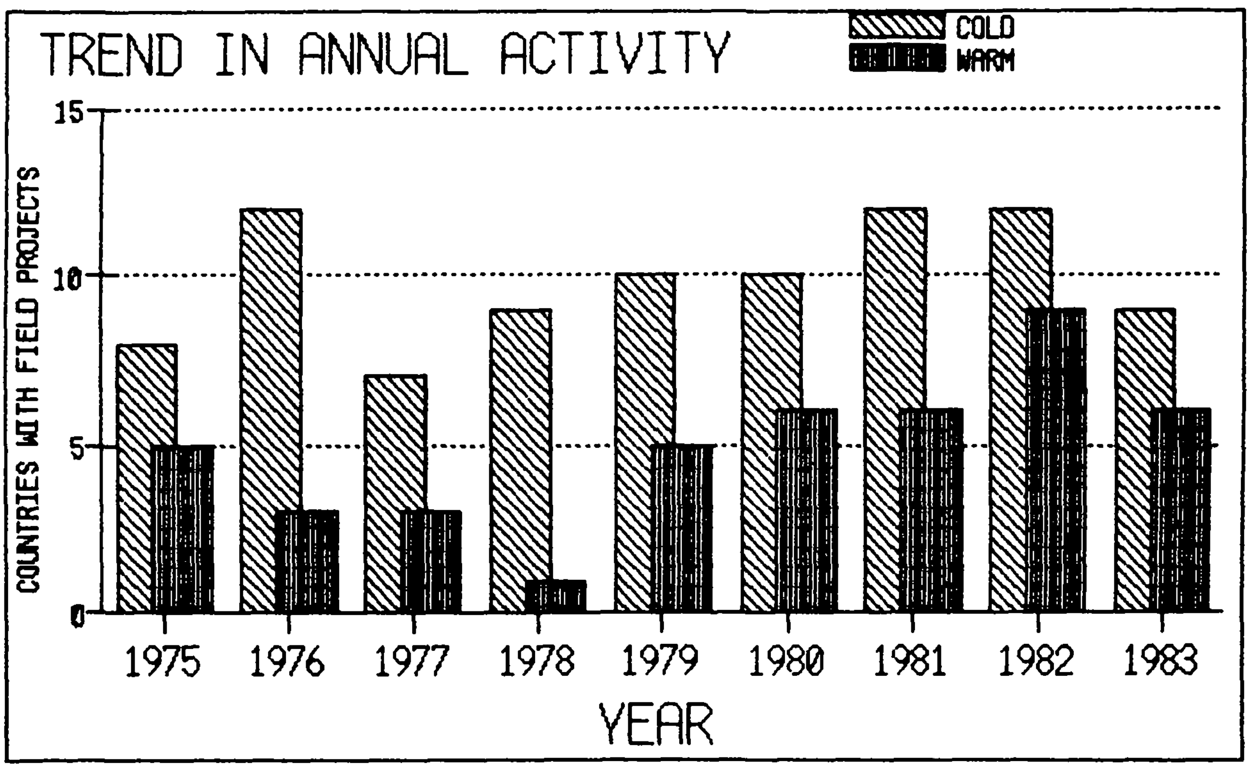


Figure 30. Trends in annual field activities in precipitation modification

4. Components of a precipitation enhancement project

(a) Survey

The extraction of water from the atmosphere by artificial means can be looked upon as a mining activity (except, of course, we are dealing with a renewable resource). One does not set about to mine a mineral without knowledge of its quantity and form at the prospective site. One needs a survey to design procedures for extraction, estimate the costs of extraction, and estimate whether the value of the product will exceed the costs of extraction. Similarly, before undertaking a weather modification project, one should complete an economic study. Just as a mining operation is site specific so is a weather modification project. The survey or cloud census should include data on the spatial and temporal properties of clouds at the prospective site, including information on their dynamic properties and their microphysical composition (the state of the cloud particles and their size distribution). From this, estimates of the amount of additional precipitation and its temporal distribution can be estimated. The accuracy of this estimate will be dependent upon how thoroughly the survey is performed and the methods used in its analysis. Unfortunatley, in any case, accuracy will not be great. The design and evaluation of the cloud survey requires expertise that is not commonly available in developing countries and is the subject of on-going research.

The survey should produce information on whether or not to proceed with a project and ideas concerning the design of a project. Figures 31 and 32 show the results of one such survey.

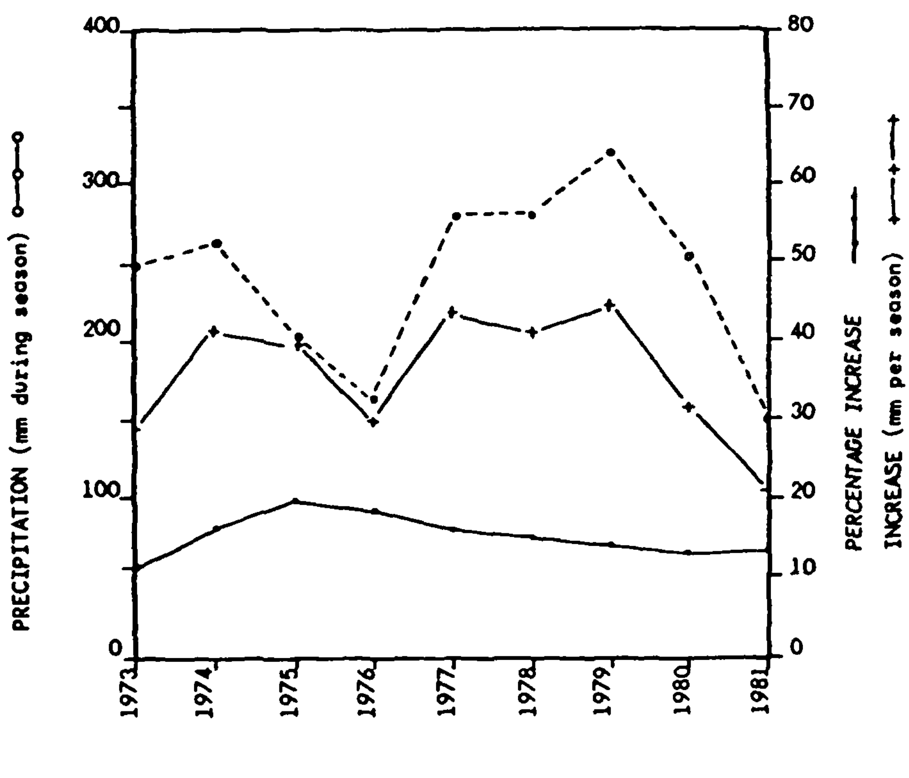


Figure 31. Annual seasonal precipitation and estimated increases using analogue approach

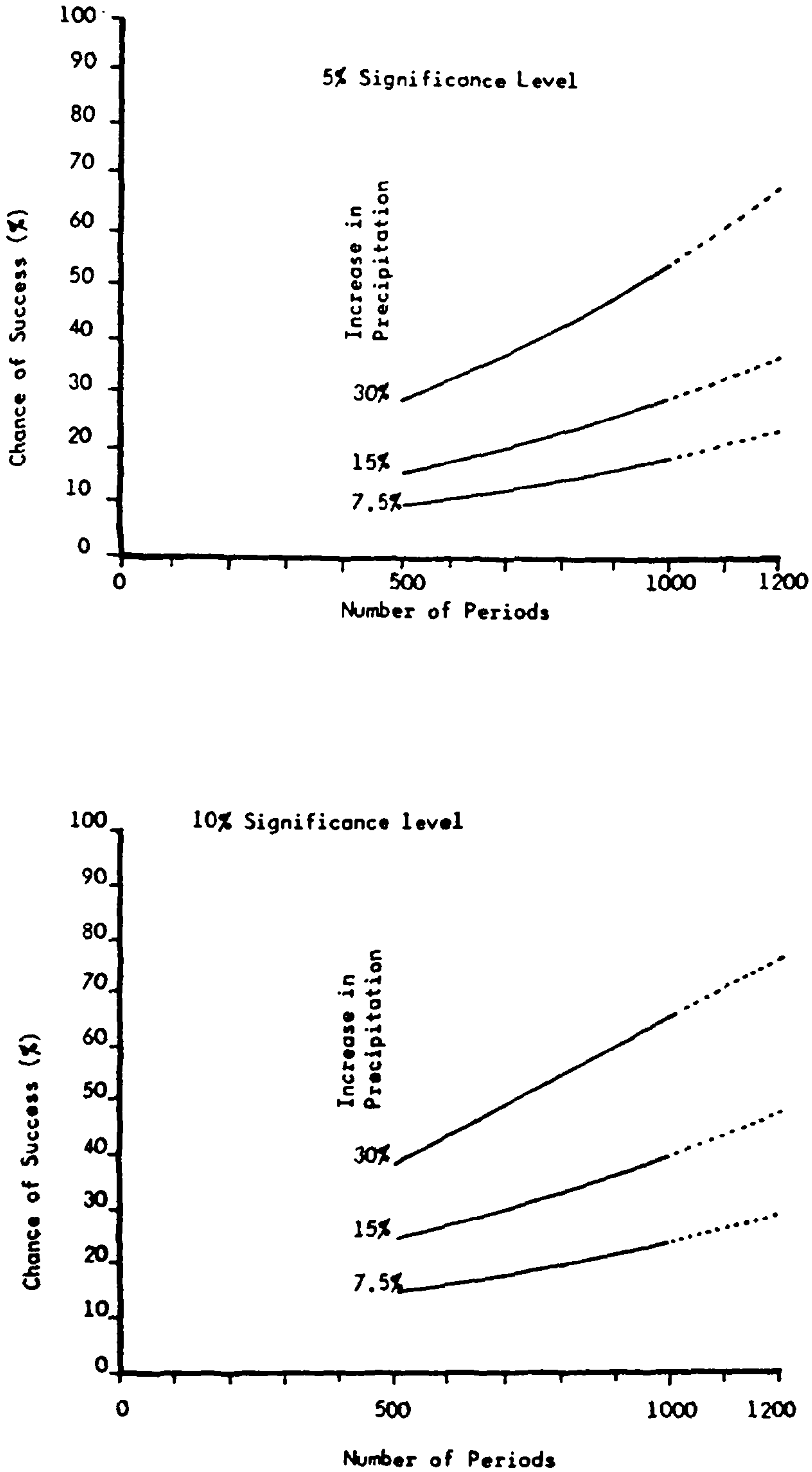


Figure 32. Expectation of a successful detection of results of an experiment

Referring to figures 31 and 32, annual seasonal (January-May) precipitation at the site of the survey (in Spain) varied from about 150 mm to 300 mm between 1973 and 1981. Considering the variation in weather during these years, it was estimated that precipitation increases varied between 11.6 per cent (1973) and 19.4 per cent (1975). Both the heaviest and lightest rainfall seasons (1979 and 1981) had projected increases of 13.9 per cent and there is little suggestion that cloud seeding could smooth the annual seasonal precipitation. Note that these are hypothetical figures based on an extrapolation of an analysis of special field observations taken in 1979 through 1981 during which no seeding took place. Note also that the analysis is not unique: other analyses of the same data suggested annual precipitation increases of less than 5 per cent.

Using the results of the survey one can estimate the length of time necessary to achieve a specified level of confidence in the apparent results. For scientific work, a 5 per cent level of significance (1 chance in 20 that the analysis is incorrect) is generally sought. For water management purposes, perhaps greater uncertainty can be tolerated. Here a 10 per cent level of significance (1 chance in 10 of being incorrect) is also shown. Approximately 5 years will be required to obtain data from 1200 periods. Applying the results above, it is unlikely that at the end of 5 years one will have gathered sufficient data to reach the desired certainty in results.

(b) Evaluation

There is too little attention to evaluation in almost all operational weather modification projects. Experience shows that it is important to incorporate evaluation procedures in the projects from the beginning.

The problem is that an experimental or observational unit (a cloud, a storm, a weather system, or simply one or more days of possible rain) is seeded with some agent, and a result is observed. This result may be a quantitative measurement of any one of several properties - cloud height and its changes, radar echo, average rainfall from a number of rain gauges, streamflow, snowpack, etc. For an observational unit two key questions should be addressed:

(i) Is the result repetitive, given similar conditions, or is it a result of chance?

(ii) Could the result be caused by factors other than seeding?

Over a period of time individual events are summed into what clients and/or operators might refer to as the result of the project. An assessment of this should address three key questions:

(i) Is the result statistically significantly different from what would have occurred without seeding?

(ii) Is the result the most likely outcome of future operations or could the likely outcome be calculated?

(iii) Does the result justify the operation?

An assessment should guide improvements in the project design but a strict, scientific evaluation permits little latitude in project operations.

If the answers to these questions are "yes", it can be concluded that the project demonstrates a weather-modification effect having economic utility. Even if one or more of the answers is negative or uncertain, the experiment will still be valuable. The essence of any design will be, in fact, to provide from the evaluation the greatest likelihood of definite, unambiguous answers to these questions.

(c) Requirements

The requirements described below are intended only to show what should be involved in the exploratory phase of a precipitation enhancement field project. In this phase the knowledge of the raw materials (weather) available will be gained and design of the operations worked out. Data will be available to make estimates of what might be achieved. This phase may have a duration of five or more years.

(i) A headquarters office to direct the project, plan day-to-day activities and to serve as a centre for in-field data evaluation. Facilities to receive all regular telex, teletype and facsimile weather broadcasts should be available. Satellite imagery reception and computer facilities to process data are highly desirable.

(ii) Rain-gauge network. This will be the primary source of data for evaluation. The greater the areal density of gauges, the greater will be the confidence in the assessment.

(iii) Seeding agent generators (air-borne, ground-based).

(iv) Aircraft (to carry generators, to make observations and measurements).

(v) Radar (to monitor weather, assist in operational decisions, and provide measurements for assessments).

(vi) Pilot balloons, radio sondes (to make measurements on vertical structure of the atmosphere, assist in operational decisions, and provide information for assessment.

(vii) Manpower. Experts in cloud physics, statistics (applied to field experiment design) and field operations and evaluation will be required.

Following the exploratory phase, assuming results warrant it, a strictly operational phase might be organized in which some requirements stated above could be reduced or eliminated.

## 5. Costs

Properly designed cloud-seeding projects are major undertakings. They frequently involve complex financial interrelationships between various agencies, so that directly assigned costs in similar programmes may differ widely. Economies may be affected by rental or leasing of equipment, sharing of such items as office or laboratory facilities, and by assigning greater percentages of labour costs to volunteer observers and studies. Cost-of-living factors relevant to the area will affect technical and clerical salaries, living and travel expenses, and supplies more than professional salaries and specialized equipment (both of which will more closely approximate international salary and price scales). The figures given here are in US dollars. They serve only as a broad example of needs and must be considered as rough estimates only. The three general financial concerns are: (a) capital costs; (b) operating costs, including the preliminary stages; and (c) cost-benefit estimates.

(a) Capital Costs

One of the largest single capital expenditures will be aircraft. If seeding from aircraft is contemplated as well as an aerial observational programme, a minimum of two aircraft is indicated, and many cloud-seeding experiments use six, eight or even more. These can range from small single-engine higher-performance models, executive and military jets capable of cloud-top seeding and observation, up to large converted passenger aircraft with ample room for cloud observation and sampling equipment. As most cloud-seeding experiments do not purchase aircraft, but often take whatever are available - usually on loan from other government agencies - it is next to impossible to assign a capital cost figure to this item. Alternatively, they may be simply rented on a seasonal, or even monthly, basis.

Also difficult to price will be whatever radar equipment is obtained for the experiment. Small, relatively inexpensive, trailer-mounted radar systems are available. They are unlikely to be of much value in the exploration phase of the project but are useful in the operational phase. Commercial weather radars are priced around $500,000. Costs depend on options and auxiliary equipment. Site preparation and installation costs will be additional. Often there are ways in which costs may be shared with other agencies wishing radar information, or transferred to operating costs by rental of the equipment, and so forth.

Excluding special financial arrangements and any building construction, total capital costs are, very roughly, likely to be as follows:

Aircraft: around $US150,000 for two fairly cheap, used planes;
Radar: around $500,000 plus $200,000 installation;
Synoptic stations: about $200,000 for five surface and two upper-air;
Rain gauges: $10,000 - $20,000 for five to ten recording, 50-100 non-recording;
Observation instruments: around $100,000, including $10,000 for repair lab;
Seeding equipment: $20,000 - $100,000, depending on type of seedingplanned;
Computer facility: $50,000
Headquarters office: $50,000, including teletype, facsimile, and various office machines.

The total comes to around some $1,300,000, an amount that could be considerably reduced through special financial arrangements, or be increased several fold if the experiment were of great scope.

(b) Operating costs

These will vary considerably, even with a set total staff involvement, as the personnel may be merely loaned to the experiment, their salaries being charged to other agencies. Even for persons paid directly, costs will vary widely with local salary levels; this is more likely to affect technician rates than salaries for professionals as the latter may have to hired from abroad. In 1976 an estimate of about $800,000 was made for annual salary for project personnel, supplies and vehicle operation expenses, aircraft operations, seeding materials, technical services such as radar operations and maintenance, synoptic weather observatons and rain-gauge network maintenance. This was approximately equal to the capital cost estimate.

(c) Summary

Capital and preliminary costs of a well designed experiment will be in the neighbourhood of $1,300,000 with annual operating costs roughly similar (i.e., $1,300,000).

These estimates apply to a project of an exploratory nature. It is possible that after a project has been in place for 5 to 10 years, if the effects of seeding become well-known and the design considered optimized, a reduction in cost may become possible, mainly through reduced monitoring.

These cost estimates might appear high in relationship to costs of some actual projects. Commonly low-cost projects provide little data on which to tailor day-to-day operations and totally inadequate data and procedures to assess results. Such projects should be avoided if the intent is to produce more water. If one must start at a minimum level, plans to upgrade the operation should be made from the beginning.

(d) Benefit-Cost estimates

It will be assumed that only operating costs will be considered in benefit-cost estimates. These have been estimated at $1,300,000; a range of $800,000 to $1,800,000 will be used in the estimates shown in table 45. The seeded area might be between one million hectares (equivalent to a square 100 km on each side) and five million hectares. Thus, annual seeding costs may range from US$ 0.80 to $1.80 per hectare for the smaller area, and US$ 0.16 to $0.36 for the larger.

The possible benefits that might accrue are extremely difficult to estimate. For this reason one should insist on a large estimated benefit/cost ratio before proceeding with a project based on economic considerations alone. Table 45 is a hypothetical benefit-cost estimate based on the above cost estimates plus the assumption of a 3 per cent increase in the value of agricultural products as a result of seeding. For some crops and areas this might be equivalent to a 10 per cent increase in rainfall. Both the precipitation increase that is possibe and the value of the additional crop is site and time specific (because of annual weather variations and annual variations in crop values). Again, these figures should be considered extremely rough.

Table 45. Examples of benefit to cost ratios for a variety of possible conditions

| | Crop type a/ | | | | | |
|---|---|---|---|---|---|---|
| Benefit/Cost criteria | 1 | | 2 | | 3 | |
| Value of crop (US$ per hectare) | 100 - 200 | | 500 - 800 | | 1,000 - 1,500 | |
| Average benefit of a 3 per cent yield increase (US$/ha) | 4.50 | | 20.00 | | 38.00 | |
| Cost (US$/ha) of seeding programme (high and low values) b/ | 1.80 | 0.16 | 1.80 | 0.16 | 1.80 | 0.16 |
| Cost, if only 50 per cent of land is under cultivation (US$/ha) | 3.60 | 0.32 | 3.60 | 0.32 | 3.60 | 0.32 |
| Benefit/Cost ratio | 1.3 | 14.0 | 5.6 | 63.0 | 11.0 | 120.0 |

a/ Crops of each type very rough gross average values based on 1968-1973, data from Canada.

Type 1. wheat, oats, barley and other cereal crops, also applicable perhaps, at low end, to hay and pasture.

Type 2. sorghum, corn, peanuts, soybeans.
Type 3. cotton, grapes, sugar cane, vegetables.

b/ High - one million hectares at cost of US$ 1,800,000; Low - five million hectares at cost of US$ 800,000.

Very few operational projects provide reliable data on the amount of water that is realized by seeding. Therefore, it is clear that benefits and non-benefits due to changes in precipitation cannot be calculated. Hence, in spite of many published figures, there is very little known about the true benefit/cost ratios of weather modification activities.

A project of at least five years' duration generally will be required to obtain sufficient data for a useful estimate of the change in precipitation that is realized.

There are many uncertainties, and it is clear that if it is necessary to be confident of attaining a benefit/cost ratio greater than one, the preliminary estimates of this ratio must be quite large.

## 6. The question of efficacy

In the early days of cloud seeding, it was believed that many types of clouds and cloud systems could be successfully modified to produce more precipitation. Today, with much more information available on the structure of clouds, it has been shown that seeding can: increase precipitation; make no changes in precipitation; or decrease precipitation.

The three possibilities are due to differences in both the artificial treatment employed and in the clouds themselves (i.e., their sizes, temperatures, growth characteristic and the size and composition of the cloud particles). If one seeks to increase precipitation, conditions that would lead to decreases should not be treated, and to optimize the project, conditions that are insensitive to seeding should also be left untreated. The question then becomes: what criteria separate the three categories? Unfortunately, the complete answer is not clear although it remains the subject of active research. However, generalities can be set down.

Two time-dependent processes are involved in precipitation: firstly, the formation and subsequent disappearance of a volume of cloudy air; and secondly, the transformation of tiny cloud droplets to much larger, precipitating particles. Simplifying, three situations can be distinguished:

(a) The cloud forms and evaporates before precipitation forms;

(b) Precipitation begins to form before the cloud completely dissipates (the cloud inefficiently produces precipitation);

(c) All the cloud condensate is converted to precipitation.

A major goal of cloud seeding is to accelerate the rate of formation of precipitation. If this can be done (and is the only effect realized) in cases (a) and (b) there is a chance to increase precipitation. In the first case, the cloud may run through its growth and decay cycle before any precipitation forms in spite of seeding and, in this case, seeding would have no effect. In the third case, where the natural cloud is completely efficient in producing precipitation, seeding would have either no effect or possibly a negative effect for it could retard the natural processes and make the cloud inefficient. Thus we can make the following classification:

(a) Non-precipitating clouds:

- (i) not usefully affected by seeding;
- (ii) produce precipitation by seeding.

(b) Inefficiently precipitating clouds:

- (i) not usefully affected by seeding;
- (ii) produce more precipitation by seeding;
- (iii) become less efficient when seeded.

(c) Clouds completely efficient in producing precipitation:

- (i) precipitation not affected by seeding;
- (ii) become less efficient when seeded.

A programme to increase precipitation should focus its attention on situations a(ii) and b(ii) (for seeding) and b(iii) and c(ii) (to avoid seeding). For efficiency, a(i), b(i) and c(i) should be avoided. Until recently, these distinctions had not been made and generally attempts were made to seed all situations. With project designs that account for these distinctions, one might expect a more reliable and predictable technology to emerge with greater artificially produced yields.

Altering the dynamic properties of clouds is another important possibility. If one can make clouds grow larger, then they process more condensate, or produce more clouds, and more precipitation might be expected. Again, an effect opposite to that sought might result from seeding. Identifying factors that distinguish these categories is a subject of on-going research in weather modification. However, some general guidelines are emerging.

With respect to the dynamic properties of the cloud, the most promising situation is one in which clouds are formed by the passage of air over a mountain barrier. These are orographic clouds. Typically these clouds grow on the windward side of a ridge and rapidly evaporate on the lee side. Given a time of passage that is too short for efficient natural precipitation formation but long enough for artificially stimulated precipitation to form, prospects are favourable for cloud seeding to increase precipitation on the windward slope.

In orographic situations there is also the possibility of redistributing precipitation by retarding the rate of precipitation formation so as to cause it to fall on the lee side rather than the windward side of the barrier. Such an operation might be intended to increase precipitation in a catchment basin on the lee side of a mountain barrier or to supply water to the precipitation shadow that often lies behind mountain ranges.

Convective clouds (including isolated and banded forms) offer another promising situation. Air parcels within these clouds often have life-times that lie in the range of the "seeding window". Logistic problems and the wide range of cumuli that commonly co-exist reduce the prospects for these clouds. However, note that seeding may cause increases or decreases in precipitation from individual clouds so a selection of specific clouds for treatment rather than the entire population may be necessary.

Synoptic scale storms are generally efficient and are not likely prospects for seeding.

With respect to the thermodynamic properties of the cloud:

(a) The response of a cloud to seeding is dependent upon the temperatures at the cloud top and base. This is due to the dependence of the growth of particles and the number of precipitation embryos on temperature.

(b) The limits of temperature for which seeding will be effective depend on the cloud type (e.g., layer vs. convective clouds).

This is an area of active research. If it serves the purpose of alerting readers to the need to know the properties of the clouds that will be dealt with, then it will serve its purpose. Note that this is the kind of information on clouds that should be gathered during the preliminary phase of a seeding project (see section 4).

## 7. Environmental aspects

Weather modification is largely environmentally benign with respect to the seeding materials; however, the release, at the ground, of massive quantities of materials used in warm cloud seeding, such as common salt, may create local problems. Silver iodide is very insoluble in water and apparently there is no problem associated with selective accumulation in living tissue.

An important possible ecological change might be the prolongation of snow cover that should result in successful projects that intend to enhance water resources by supplementing natural snow packs. A 10 per cent increase in snowpack might delay complete spring melting by one or two weeks, a delay that might result in changes in flora and fauna. A successful project oriented toward farming might also result in changes in agricultural practices.

It is clear that there is necessity to identify possible environmental effects and to take steps to monitor them should a long-term project be anticipated.

Extra-area effects may pose problems. One should be prepared for effects of a successful change in precipitation in the desired ("target") area to be felt outside of this area (either a net increase or decrease outside the target is possible). These are commonly termed extra-area effects. The project needs to monitor a sufficiently large area to know the size of the effect produced as a function of location (i.e., establish the total area of effect).

Socio-political aspects are culturally dependent and should be considered during the planning of any weather modification activity. Certain countries have laws regulating weather modification, while others do not. Any legal arrangements should take into account the need for more research, the uncertainties of weather modification and the likelihood for significant future changes in the area.

The sought after effect, the modification of the amount or location of fall of precipitation typically lies within the range of natural variation. No permanent change in precipitation, if a project were terminated, should be expected. However, controls must be in place to ensure that operations do not contribute to weather-related disadvantages, for example, excess soil moisture, incuding flooding.

## 8. Where to obtain help

The World Meteorological Organization (WMO) maintains a weather modification programme having as objectives, among other things, to promote sound scientific foundations for weather modification, to provide guidance to member countries on the rationale underlying all aspects of weather modification and to facilitate training and exchange of information on both operations and research in the field of weather modification. WMO will assist members to the extent resource permit.

Text and source books dealing with atmospheric physics, and especially cloud physics, generally discuss weather modification. There are also several books dealing exclusively with weather modification. The bibliograhy contains a sampling of books that offer a pathway to more information.

Professional societies, such as the American Meteorological Society, publish material on weather modification. The Bulletin of the American Meteorological Society contains listings of consultants.

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## Appendix: Excerpts from "Review of the present status of weather modification"

(Adopted by WMO Executive Council XXXIII in 1981)

### 1. Introductory remarks

It is impractical to modify weather by competing directly with the energies prevailing in the atmosphere, except locally. Instead, points of instability are sought whereby a relatively small disturbance in the system can substantially impact the natural evolution. For example, populations of cloud drops in some layer clouds may persist for long periods without growth or sedimentation. Introduction of giant cloud condensation nuclei or water drops into such a cloud might result in precipitation by causing an accelerating sequence of collisions and growth among the drops. In the case of clouds at temperatures colder than 0°C, the introduction of artificial ice nuclei (e.g. through silver iodide seeding) or ice crystals (e.g. through solid carbon dioxide (dry ice) seeding) can result in the rapid growth of ice at the expense of numerous small supercooled water drops. In addition, the formation and growth of larger numbers of ice particles (by heavy seeding) may release sufficient latent heat to significantly increase buoyancy in the cloud and thereby enhance precipitation.

The ability to influence cloud microstructures in the ways indicated above has been demonstrated in the laboratory, and verified through physical measurements in some simple natural systems such a fogs, thin layer clouds and small cumulus clouds. However, evidence that precipitation, hail, lightning, or winds can be significantly modified by artificial means is quite limited. It is now realized that the complexity and variability of clouds result in great difficulties in understanding and detecting the effects of attempts to modify them artificially. Thus, some of the optimism of the 1950s has given way to a more cautious approach. As knowledge of cloud physics and statistics, and their applications to weather modification, has increased, new assessment crieria have evolved for evaluating cloud seeding experiments. The development of new equipment, such as aircraft platforms with micro-physical and air-motion measuring sytems, radar (including Doppler), satellites, rain-gauge networks and mesoscale network stations, has introduced a new dimension. Equally important are the advances in computer systems that permit large quantities of data to be processed. New data sets, used in conjunction with increasingly sophisticated numerical cloud models, help in testing various weather modification hypotheses.

Since the effects of artificial seeding on clouds and on precipitation are within the range of natural variability, statistical analysis is generally necessary to provide a measure (in probabilistic terms) of the strength of evidence for or against seeding effects. Although the power and scope of statistical evaluations for analysing cloud seeding effects is steadily improving, pitfalls exist. Statistical evaluations based on random experiments are considered the most reliable. In the case of precipitation modification, target/control areas may be suitable if their rainfalls are highly correlated. Multiple control areas may be necessary to assess chance trends in surrounding areas that parallel seeding effects. In most cases, experiments must run for several years to achieve a statistically significant result. Measurements and statistical analysis of variables such as ice particle concentrations, radar reflectivities, precipitation rates in the cloud, rainfall on the ground, in seeded and unseeded cases can serve not only to shorten the time required for conclusions to be drawn from an experiment, but will also provide data to examine the physical plausibility of a result. Background studies in the experimental area are required in order to determine the importance of, and correlations between, variables. Historical statistical comparisons are suspect because they may involve intercomparisons of inconsistent data sets. Also, insurance values and projected crop yields are not considered satisfactory test variables.

Viewed from these perspectives, most of the past weather modification experiments are considered inconclusive by the scientific community. Careful evaluations, involving both extensive physical measurements of the clouds and precipitation and statistical analyses of the measurements are now considered mandatory in arriving at sound judgements. At this time, weather modification other than supercooled fog disperal must be considered in the realm of research. Enhancing precipitation or suppressing hail reliably and on demand remain distant goals.

Many operational programmes are conducted with recognition of the risks inherent in unproved technology. For example, there are indications that under certain conditions seeding may cause less rain in the target area, or more hail and decreased precipitation accompanying the hail. Unfortunately, operational programmes are seldom conducted in a manner that allows scientific evaluation.

Brief summaries of the current status of weather modification in several categories are given in the following section. The general criteria for evaluating the results of cloud seeding will be as outlined in this preamble. Only those weather modification activities are considered that appear to be based on sound physical principles and which have been tested in the field.

## 2. The enhancement and redistribution of precipitation from supercooled clouds

Many natural clouds are supercooled, in other words, they contain liquid droplets at temperatures colder than 0°C. Natural freezing nuclei, present in highly variable amounts, facilitate the freezing of some cloud droplets into ice crystals. These crystals, usually a small minority among all the cloud particles, then grow at the expense of the droplets, and so tend to lead to precipitation of the cloud. If the concentration of the natural nuclei, and thus of the crystals which result, is very small, the process of precipitation can be very slow, and it is in such cases that the introduction of artificial nuclei (typically crystals of silver iodide) is thought to be effective. Such additional nuclei would speed up the process of precipitation in the cloud and augment the amount of precipitation (snow or rain) that falls out of the cloud.

The freezing of cloud water implies the release of latent heat of freezing, and this in turn adds positive buoyancy to the cloud. If there are enough nuclei to freeze all the cloud droplets, the cloud will quickly glaciate (become an ice cloud).

The introduction of artificial nuclei (seeding) is thus motivated by one or more of the following expectations:

- That the precipitation process in the cloud is accelerated and that more cloud water is converted into precipitation;

- That the buoyancy created will have desirable dynamic effects on the cloud;

- That the cloud is glaciated, which may effectively terminate or postpone the precipitation process.

An order-of-magnitude argument may be given for the minimum mass of reagent (for example AgI) that is needed to produce rain in the absence of other nuclei. One gram of silver iodide can be divided into some $10^{14}$ crystals. Assuming that these can be widely distributed in space, and that each of them becomes the nucleus of a particle which ultimately grows into a raindrop 2.5 mm in diameter, more than a million cubic metres of rain would result. Distributed over an area of 1000 $km^2$, this would be the equivalent of 1 mm of rain. In the light of this type of argument, and because, in many regions of the world, a large proportion of clouds are supercooled, this seeding technique has attracted the greatest number of attempts at precipitation enhancement.

Several major experiments have been conducted in various types of cloud systems, including orographic, winter convective and summer convective clouds. Some of these have provided either statistical or physical indications that seeding may have affected precipitation. To date only one cloud-seeding experiment has combined physical evidence in support of a seeding hypothesis with persuasive statistical evidence of increases in precipitation over an area. That project, carried out on winter convective clouds in Israel during two consecutive experiments over a 15-year period, resulted in an apparent precipitation increase of about 15 per cent.

There is some evidence that certain sub-tropical convective clouds become taller and larger when they are heavily seeded to release latent heat. In view of the high correlation between the size of convective clouds and rainfall from them, the seeded clouds presumably give more rain than if they had been unseeded. Confirmation that areal precipitation can be increased in this way is required from suitably designed experiments.

A question that commonly arises is whether seeding in one area to increase precipitation might inadvertently produce changes (decreases are most often mentioned) in precipitation outside of the target area. No firm statistical or physical evidence is available on this point.

There is some physical evidence that deliberate heavy seeding (so-called overseeding) of clouds in certain topographical situations can result in the diversion of snowfall (up to 50 km). However, seeding trials of this type have not been subjected to statistical evaluation.

## 3. Modification of rain from warm clouds

In tropical or sub-tropical countries many potential rain-producing clouds are convective in nature with tops often not exceeding the height of the freezing level. Hence, the possibility of increasing rainfall from such warm clouds by enhancing the efficiency of the collision-coalescence process has generated considerable interest in these regions.

In some warm clouds the development of large droplets may be sufficiently slow to delay the onset of significant growth by collision-coalescence until the cloud has passed its mature stage. In principle it is possible to enhance precipitation from such clouds by seeding them with hygroscopic particles or water drops to hasten the growth process. However, only a limited number of experiments have been carried out to test the effectiveness of these techniques. One problem is that large masses of seeding material are required. For example, if seeding is carried out with 10 mm-diameter salt particles of density 2 $g/cm^3$, and each particle ultimately grows to a raindrop of 2.5 mm diameter, over 100 kg of salt would be required to produce one million cubic metres of rain (equivalent to 1 mm of rainfall over an area of 1000 $km^2$). Even for this modest result, it has been necessary to assume a more favourable growth ratio than is likely to occur in practice. The situation would be much more favourable if a "chain reaction" occurred in which drops break up after first growing by coalescence to a large enough size, and the fragments then served as growth centres for new large droplets. More direct evidence is needed to establish the importance of such a process in natural clouds. In spite of these limitations, a few encouraging (but not conclusive) experiments have been carried out. None have the requisite combination of successful rainfall increases based on physical and statistical evidence.

## 4. Economic, social and environmental aspects of weather modification

Weather modification is sometimes considered when there is a need to improve the economy of a region by increasing water resources for agricultural use, water supplies for cities, or for hydroelectric power generation. In deciding whether to apply such techniques, it hardly needs to be emphasized that the benefits of modification should be larger than the costs of a weather modification operation. However, in considering benefits to some segments of the population, losses to other groups must also be weighed, together with possible compensation schemes. For example, whereas one type of crop may benefit from more rain, another may not; more rain may be good for agriculture but not for a flourishing tourist industry in the same area; bigger crop yields may lead to lower prices and reduced profitability of some farm operations. Thus, it is necessary to consider not only the economics of the segment that desires a certain type of weather modification, but the overall net effect on the whole community.

Precipitation enhancement has to be viewed from the over-all aspect of total water resource management. It may be difficult or impossible to ameliorate drought conditions when they occur. In most droughts, clouds suitable for seeding are normally scarce. Replenishing aquifers with water (which can be pumped to the surface if needed) or filling reservoirs and augmenting snowpacks is obviously easier because the timing of precipitation is not crucial. Thus, changes in agricultural practices, with conversion to storage and irrigation, may be needed.

Wherever weather modification causes economic conflicts, problems of a legal nature may arise. Besides, weather modification activities within the boundaries of a particular state may be perceived by a neighbouring state as having adverse effects within its borders (the so-called "extra-area effects", that in this case are alleged to go beyond the boundaries of the state carrying out weather modification activity).

Some countries already have provisions for regulating the conduct of weather modification activities, while the international community is developing guidelines for resolving international conflicts arising out of weather modification activities. However, it must be emphasized that weather modification still remains in the realm of research. Any legal system aimed at regulating weather modification at the international level must be developed hand in hand with scientific knowledge in the field.

The implications of any projected long-term weather modification operation on ecosystems need to be assessed before long-term, large-scale operations are undertaken. Such impact studies could reveal changes in the balance of economic benefit. During the operational period, monitoring of possible environmental effects should be undertaken as a check against estimated impacts.

## B. Conceptual evaluation of "static" and "dynamic" seeding modes based on recent analyses of Israeli II and FACE 2 Experiments

by A. Gagin*

### 1. Introduction

In properly designing cloud seeding experiments, due consideration should be given to the need for providing data for subsequent analyses, which will enable the testing of the basic physical hypotheses underlying these experiments. While it is important to record the effects of seeding on rainfall "on the ground", the statistical evaluation of this parameter alone cannot constitute an acceptable result of a successful seeding effect.

In attempting to provide such physical substantiation it is possible to adopt one of the following two general approaches:

(a) That which requires that each step in the chain of events leading to precipitation formation in the treated clouds is specified in advance within the framework of a detailed conceptual model, and is later verified by observations in order to document in quantitative terms the causes and their effects.

(b) That which defines the conditions which are conducive to positive seeding effects, based upon a more general conceptual model, resting on previous studies of cloud microphysics and the general aspects of the dynamics of the clouds and cloud systems involved, and tests the results, by physical stratifications of the experimental data, for their physical plausibility with adequate statistical methods.

While the first of those two approaches is used to establish the physical basis for rainfall enhancement techniques and hence is very basic, expensive and time consuming, the second is obviously more risky. It requires, however, few facilities and less highly skilled human resources, and it can provide quicker answers at a reduced cost. The crucial factor relating to the latter approach is the complexity of making sound physical hypotheses on the basis of circumstantial scientific evidence only. It would be appropriate to point out that the second approach cannot be a substitute for the first but rather, ideally, it should be applied to simialr rainfall regimes, in order to facilitate the transfer of knowledge gained in the conduct of the basic studies by the first approach.

The High Plains Co-operative Program in the Western United States (HIPLEX I) was the first to design and attempt to apply this basic approach. Unfortunately it was prematurely terminated and hence did not complete its very important task to fulfill the objectives that are so badly required.

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The present report is an attempt to evaluate conceptually the validity of some of the basic hypotheses underlying the techniques of cloud seeding aimed at increasing rainfall by either producing microphysical "static" effects in the treated clouds, or by triggering "dynamic" changes in them. This attempt will rely on data and analyses obtained in experiments performed with the second approach as it relates to such past experiments as Israeli II and the Florida Area Cumulus Experiments (FACE-2), correspondingly.

## 2. Evaluation of the basic postulates of "static" seeding as inferred from analyses of Israeli II

Cloud seeding, aimed at the production of static effects on cloud microstructure for rainfall enhancement, has been applied in the two consecutive long term, randomized experiments referred to as Israeli I and Israeli II. Over-all target daily rainfall, over the whole target areas, was found to increase under seeding by about 15 per cent in Israeli I (Gabriel, 1970; Gagin and Neumann, 1974) and by about 13 per cent in Israeli II (Gagin and Neumann, 1981). These results were significant at less than 5 per cent. Such confirmation of the results has been found to occur also in sub-areas of the total target areas, located at roughly the same distance from the line of aircraft seeding. At these locations and experiments the positive effects were found to be 24 per cent and 18 per cent respectively. In these latter cases the statistical significance levels of the results were even higher, i.e. they were less than 3 per cent.

At the outset of each of these experiments, Neumann, Gabriel and Gagin (1967) made the following two assumptions:

- The so-called ice-crystal mechanism is the most efficient precipitation forming process for the given regional meteorological conditions, that natural ice nuclei are responsible for the initial formation of precipitation embryos and that conditions exist for seeding at the time when the deficiency of a certain critical concentration of ice crystals is the reason for delay, or even failure, in precipitation initiation.

- Silver iodide (AgI) smoke was selected as the seeding agent. This implied a hope to achieve rain stimulation by ice-crystal formation, either through making the existing process of rain formation more effective, or through inducing precipitation formation in clouds that otherwise would not have precipitated naturally.

The rather extensive physical studies, accompanying the Israeli experiments, summarized by Gagin (1981), have shown that winter east Mediterranean clouds are significantly continental in nature, that the broadening of cloud droplet spectra, in these clouds, can be attributed to condensation alone, and that these clouds are totally deficient of large drops at all altitudes, a fact indicative of the absence of an efficient collision coalescence process (Gagin and Neumann, 1974). Furthermore it was found (Gagin, 1975), that in all probability precipitation elements form in these clouds by the combined processes of ice crystal formation and growth by vapour deposition and subsequently by accretion. The graupel particles resulting from these processes have been found to have, at least initially, low density, porous structures. Their concentrations have been found to be roughly an order of magnitude less than that of ice crystals, just below the tops of clouds having summit temperatures warmer than -21°C. Both ice crystals and graupel concentrations have been found to have a clear dependence on cloud summit temperature. Graupel concentrations fell below the detection limit of our instruments ($10^{-3}$ $lit^{-1}$) over the temperature range of cloud top temperatures of -3 to -11°C. More recent studies (Gagin, 1982), utilizing a vertically pointing radar and a distrometer, indicate that raindrop concentration on the ground, at elevations of roughly about 1 km below the 0°C isotherm, depend on cloud top temperatures aloft in a manner resembling that of the dependence of graupel concentration on summit temperatures.

In concluding from the above summarized studies, it can be stated that the cumulus clouds treated in the Israeli experiments, which are organized in cloud fronts, post-frontal bands or in Benard-cell patterns, having a summit temperature range between -10°C to -25°C, can be considered to be colloidally stable entities which require, as a necessary condition, the existence of suitable concentrations of ice crystals which should enjoy adequate growth conditions in order to produce rain.

One of the salient results of Israeli II (Gagin and Neumann, 1981), is that the treated clouds responded positively to seeding in a manner which depended systematically on cloud top temperature. Thus, on days when the modal values of the clouds' distributions had top temperatures of -15°C to -21°C, maximal effects of about 46 per cent precipitation increase have been recorded, a result statistically significant at less than 1 per cent. These experimental results have been preceded by theoretical studies which actually predicted these effects: Neumann, Gabriel and Gagin, 1967; Gagin and Neumann, 1974; and Gagin and Steinhorn, 1974.

While both the direct results of the physical studies (Gagin, 1975) and the results of the statistical analyses of the seeding experiments provided a reasonably acceptable corroboration of the first of the above-stated assumptions, the following summary of recent results will be an attempt to relate some findings in support of the second of the assumptions.

The components determining total daily rainfall, at any given locality, such as the durations, intensities and the numbers of clouds responsible for these rainfalls, are obtainable from the charts of the recording rain gauges installed at that place. Statistical analyses applied to daily means of the cumulative values of rain duration, number of rain events and their corresponding rainfalls, as they are inferred from representative charts of the recording rain gauges scattered in the control and target areas, can provide a clue to the understanding of the differential effects of seeding on these components. Definite and statistically significant results related to these factors will also enable us to check the validity of the second of the assumptions made above. Thus an increase, due to static seeding, of the number of rain events could be interpreted as an effect of rain initiation in clouds that otherwise would not have precipitated naturally. Additionally, an increase in rain duration, beyond that resulting from the increased number of rain events, can be taken as an indication of an effect of static seeding on the already precipitating clouds by increasing their precipitation efficiency.

(a) The effect of seeding on the components of rainfall

(i) A short résumé of the design of Israeli II

Since this study was conducted within the framework of Israeli II, it seems appropriate to summarize some of the salient features of the design of that experiment. The Israeli II randomized seeding experiment was conducted during the six winter rainfall seasons of 1969-1975. Its primary purpose was to examine the possibility of enhancing rainfall by static cloud seeding over the Lake Kinneret Catchment Area (LKC), see figure 33. The test hypotheses for this experiment, the criteria for defining the conditions suitable for seeding and the details of the design of Israeli II are given in Gagin and Neumann (1981). The total number of experiment days was 388, of which 209 days were randomly allocated to seeding and the rest were allocated to remain unseeded. Allocations were carried out, at a probability of 0.5 in both cases, in such a manner that they were independent from day to day.

A table of random allocation of dates, without blocking, for each season was made before the beginning of each season by the project statistician. This list was known to all involved in the actual operations of the experiment, but not to the rainfall observers of the Israeli Meteorological Service who are totally independent of the experiment and therefore can be regarded as "blind" to the seeding operations. However, it should be noted that the experimental design required that in every case where a day allocated to seeding was not actually seeded (e.g., because no suitable clouds developed or for any other reason), the days were counted as seeded. While this requirement obviously resulted in a reduction of the overall positive result of the experiment, it was considered an efficient way to remove any selection bias.

Since any effective statistical design requires a control area, we had to reserve the country's Mediterranean coastal area as a control area (C). The control area had to be west of the target, since in Israel on all days of rain the winds at cloud-base level and above always have a westerly component (figure 33).

Since the Israeli experiments applied the so-called "static seeding technique", it was thought that routine observation of cloud-top heights and temperatures could provide daily distributions of these elements to enable the scientist, through stratification analyses to (1) test some of the hypotheses with regard to the physics of precipitation processes and the effect of seeding on them; (2) break down the overall results in order to detect whether there was some physically systematic set of results that would provide physical plausibility to the statistical results (physical plausibility is more vital than mere statistical significance); and (3) give some indication, perhaps, of the relative efficiency of cloud seeding on clouds with different properties.

Some details of the distribution of cloud-top heights and their temperatures on days with different daily amounts of rainfall are given in Gagin and Neumann (1974) and in Gagin (1981). The daily modal values of these distributions, or the corresponding modal value of the temperature of cloud-top heights, were used in stratifying the days into sub-groups of experimental units in order to study the differential effects of seeding on the various cloud populations (Gagin and Neumann, 1981).

(ii) Data reduction and processing of measurements taken by recording rain gauges

Figure 34 shows a typical chart of a recording rain gauge representing the rainfall on 14 March 1984. The various rain events on that day were numbered consecutively. The integrated duration of rainfall for all 14 rain events was 164 minutes and the total amount of rainfall precipitated at that station on that day was 14.5 mm. Since most, if not all, rainfall in Israel is produced by cumuliform clouds, the distinction between various rain events is fairly straightforward and rather simple.

In the analyses described below, data were gathered and processed for all 388 days of Israeli II. Control rainfall characteristics have been represented by four rain-recording stations and the LKC by six such stations. The details of their area distribution are shown in figure 33. In view of the exceptionally high correlations of daily rainfall between stations within any of the experimental areas and those between the control and the LKC (Gagin and Neumann, 1981), and considering the magnitude of the effect required for data reduction for 388 days, it was felt that a relatively small number of stations would suffice to provide reliable measurements of daily means of rain properties for the two areas in question, i.e. the Control and the LKC. Since the LKC was the core target of Israeli II, it was therefore decided to restrict this study to an evaluation of the results in the LKC only. Table 46 gives the daily mean values of rainfall (R) in mm, its duration (D) in hours and the related number of rain events (P) in the Control (C) and LKC under conditions of seeding and no seeding. While the formal results of the Israeli experiments can and should refer only to days allocated to seeding, independently of whether the clouds on these days were seeded or not, we included in table 46 the means of these three parameters also on days allocated to seeding and actually seeded.

These latter values appear in parantheses in the table. For the sake of comparison, the daily means of rainfall, as obtained from a much larger number of stations having only daily read rain gauges (Gagin and Neumann, 1981), are also given in table 46.

As can be easily seen, the difference between them and those obtained from the recording rain-gauge data, are really quite minute.

(b) Results

(i) Over-all statistical analyses

The seasons and experimental units used in this study are exactly those used in the previous analyses of Experiment II (Gagin and Neumann, 1981).

Table 46 presents the mean daily values of R, D, and P as defined above. This table also gives the numbers of experimental days allocated to seeding and of those that were actually seeded for both the C and LKC areas. As in

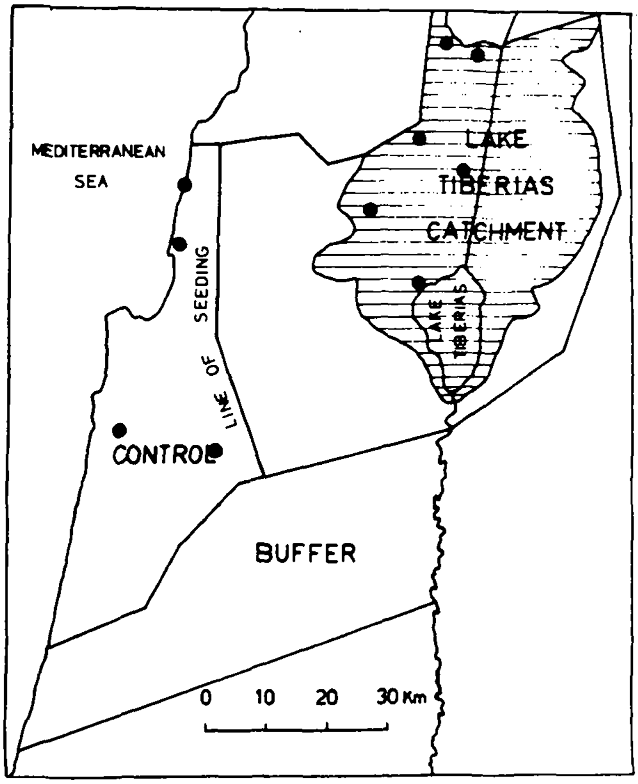



Figure 33. Location of recording rain gauges in Israel

Notes:

(1) Circles denote recording rain-gauges
(2) Hatched area defines Lake Kinneret Catchment Area
(3) Line of aircraft and seeding indicated

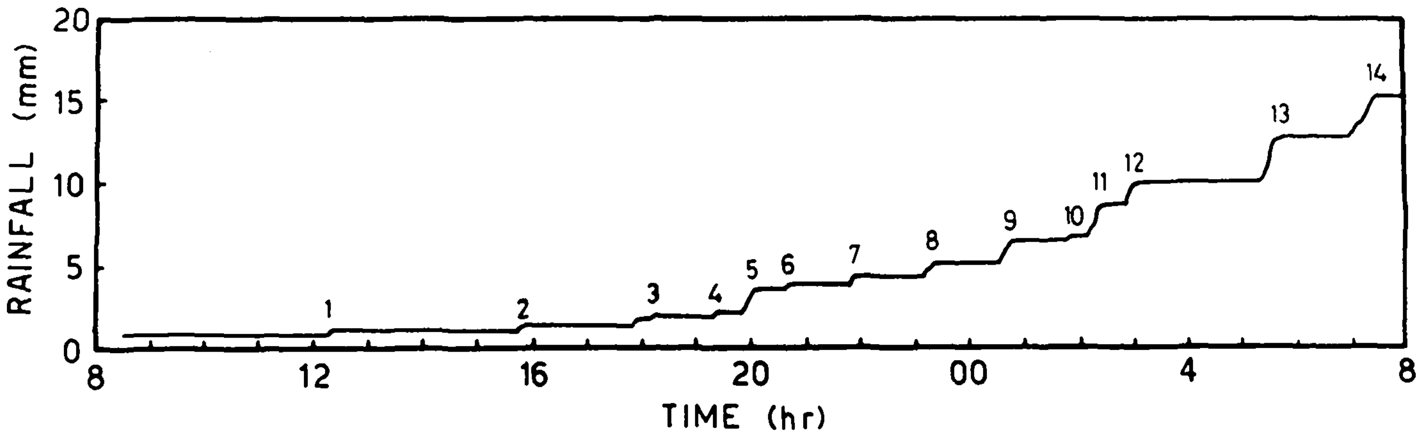



Figure 34. Chart of a recording rain gauge

Table 46. Over-all mean daily rainfall parameters for the Control and Lake Kinneret Catchment Areas (LKC)

| Parameter | Mean seeded | | Mean unseeded | |
|---|---|---|---|---|
| | LKC | Control | LKC | Control |
| R-Rainfall Recording rain gauges (mm/24 hours) | 8.82 (10.32) | 8.36 (9.51) | 7.24 (7.24) | 8.57 (8.57) |
| D-Duration (hrs) | 2.21 (2.59) | 1.58 1.80) | 2.18 (2.18) | 1.83 (1.83) |
| P-Number of rain events | 6.17 (7.20) | 6.99 (7.50) | 5.61 (5.61) | 7.32 (7.32) |
| Rainfall-Daily rain gauges (mm/24 hours) | 8.89 (10.39) | 8.30 (9.54) | 7.32 (7.32) | 8.05 (8.05) |
| Number of experiment days | 209 (174) | 209 (174) | 179 (179) | 179 (179) |

Source: A. Gagin and J. Neumann, "The Second Israeli Randomized Cloud Seeding Experiment: Evaluation of the Results," Journal of Applied Meteorology, (20:1981:1311).

Note: These data were obtained from recording rain gauges, on experiment days which were either allocated to seeding or no seeding or allocated and actually seeded. Also given are the means of rainfall as inferred from daily read rain gauges. The numbers in parentheses refer to days allocated to seeding and actually seeded.

Experiments I and II the experimental days were selected according to the criteria specified in Gabriel (1970) and Gagin and Neumann (1981). It is noted that for every rain parameter (R, D and P), the mean daily Control values on days allocated to be unseeded (Cn) are greater than those for the days allocated to be seeded (Cs). Based on the high correlation between Cn and LKCn, the Double Ratio, as adopted before launching Experiment II, estimates the effect of seeding on any test variable by compensation for any systematic effects which may have resulted from the choice of the specific C and LKC areas and of the natural changes introduced by the random selection of days for either seeding or no seeding. Thus the Double Ratio is defined in equation (1) as:

$$\left[ (DR)_j = (LKCs)_j/(Cs)_j \right] \cdot \left[ (Cn)_j/(LKCn)_j \right] \qquad (1)$$

where Cs and LKCs are the mean daily values obtained, for any of the (j) parameters R, D and P on days allocated to seeding. Equally, Cn and LKCn for any of these (j) parameters have been defined above. It should be noted that the DR should equal unity if seeding had no effect and if the sample is sufficiently large.

The level of the randomization significance level of the DR (Gabriel and Feder, 1969) (one-sided test), was obtained from 1000 random permutations of the data. The significance of the observed DR was estimated by the per centage of cases in which the computer permutation experiments gave a DR equal to or greater than that observed in the actual seeding experiments. It is seen from table 47 that the excess of the DR over 1, in the case of R and D, is at least twice as large as the standard error (SE). This difference is also reflected in the signifiance levels. The effect of seeding on the total daily mean number of rain events, though positive, does not seem to be significant. The levels of significance (table 47), of the effect of seeding in the LKC on both the daily recorded rainfall, of about 25 per cent and on the mean daily duration of rain, of about 18 per cent, are highly significant, i.e., at the levels of 0.6 per cent and 1.8 per cent respectively.

The question why the apparent positive effect of seeding on the over-all daily mean number of rain events does not appear to be statistically significant will be dealt with in the following section.

(ii) Stratification of the data by cloud-top temperatures

We have pointed out in several earlier papers (Gagin and Neumann, 1974; Gagin and Steinhorn, 1974; and Gagin, 1975) that in winter cumulus clouds, such as those in Israel, the time element for the possible growth of precipitation elements is of crucial importance. Crystal growth by deposition, followed by graupel formation, by accretion and the subsequent growth of the latter by riming, provide the most suitable, and probably the only, vital mechanism for precipitation formation. Since the onset of riming requires that the ice crystals should attain some minimum size before they become able to collect cloud drops (which also must exceed some minimum size in order to be collected) and since ice crystal growth is a non-linear function of temperature with the major, rapid growth domain occurring at about -15$^{o}$C, the time and growth rates available for growth of the very small

Table 47. Double Ratios (DR), standard errors (SE) and randomization significances pertaining to rain parameters of Lake Kinneret Catchment and Control Areas

| Parameter | Mean seeded | | Mean unseeded | | DR/SE | Randomization significance level (%) |
|---|---|---|---|---|---|---|
| | LKC | Control | LKC | Control | | |
| R-Rainfall (mm/24 hrs) | 8.82 (10.32) | 8.36 (9.51) | 7.24 (7.24) | 8.57 (8.57) | 1.25/(0.09) (1.28)/(0.10) | 0.6 (0.1) |
| D-Duration (hrs/24 hrs) | 2.21 (2.59) | 1.58 (1.80) | 2.18 (2.18) | 1.83 (1.83) | 1.18/(0.08) (1.21)/(0.09) | 1.8 (0.4) |
| P-No of rain periods | 6.17 (7.20) | 6.99 (7.50) | 5.60 (5.60) | 7.32 (7.32) | 1.15/(0.16) (1.25)/(0.18) | 17.7 (8.1) |

Notes:

(1) Double Ratios calculated using equation (1).
(2) The numbers in parantheses refer to days allocated to seeding and actually seeded.

number of naturally occurring ice crystals, i.e., crystals nucleated at about -10°C, are insufficient to render them large enough to become precipitation elements capable of falling through the updrafts in clouds with tops which are not much higher than the -10°C isotherm, i.e., -12°C. If, however, the clouds are deeper, to include the -15°C rapid growth domain, the crystals forming naturally at -10°C are rendered large enough to survive evaporation at the tops of these taller clouds and subsequently will enable them to reach the ground as noticeable rain. The authors have therefore suggested in their earlier papers that static seeding (as practiced in Israel) of winter continental cumulus clouds could initiate rain in clouds that otherwise would not have precipitated, i.e., clouds with tops warmer than about -10°C to -15°C. This can be realized by the formation of ice crystals at lower elevations in the clouds, where the temperature is close to -5°C, the threshold of activation of AgI. Thus, seeding with AgI will form ice crystals which will enjoy additional growth conditions and will hence reach graupel sizes that will finally reach the ground as rain.

It is recognized that such an effect will contribute relatively less to the total possible increase in rainfall which can be achieved by seeding also the bigger clouds, since such shallow clouds precipitate less than the deeper and colder clouds. We have therefore also suggested that static seeding could be particularly effective in clouds which are colder than -15°C, which already contain some naturally grown graupels, either by forming additional, early grown graupels, or by increasing the already existing numbers of graupel particles. In both cases all will enjoy the dendritic growth domain of about -15°C at some distance below the cloud tops, i.e., in clouds with top temperatures of about -15° to -20°C. Our calculations have further shown that clouds with tops colder than -20°C are less amenable to seeding of this type, becaue of the rather efficient manner by which they naturally produce precipitation elements, in numbers and sizes such that the rate of water consumption as they grow exceeds the rate of condensate formation at these higher and colder elevations.

These postulates have been corroborated by an overall analysis (Gagin and Neumann, 1981) of daily rainfall data obtained from a network of daily measuring stations. In this study days have been classified according to the modal value of the daily distribution of cloud-top temperatures. This stratification of the data revealed a rather systematic behaviour of the results: for the group of days with modal cloud-top temperatures within the range of -15° to -20°C, the results indicated a maximal positive effect under seeding of about 46 per cent significant at the 0.5 per cent level. Extension of the group of days to include all days in which the modal value of cloud-top temperatures was between -11 to -21°C resulted in an apparent increase due to seeding of 29 per cent significant at the 0.8 per cent level. On the other days when the modal values of cloud-top temperatures were either warmer than -10°C or colder than -21°C, the effects of seeding were found to be insignificant.

Table 48 gives the breakdown of the results according to the same classification used in Gagin and Neumann (1981) and partially quoted above, but for daily rainfall, as extracted from the recording rain gauges distributed in the LKC and the Control (C). Not surprisingly table 48 reveals the same pattern of results given in Gagin and Neumann (1981). In the present study, however, the effects of seeding on daily rainfall seem somewhat larger and the significances are quite high but not as high. It should be noted that the present results pertain to the LKC with the Control, whereas Gagin and Neumann's (1981) results relate to the totality of the northern target area. In the latter study the LKC was shown to have received greater effects (18 per cent in LKC and 13 per cent in the north). Thus, the over-all positive effect, under seeding in the LKC, was found to be about 53 per cent and 45 per cent on days when the modal clouds were in the range of -15 to -21°C respectively.

Table 48 gives the breakdown of the results of seeding in the LKC pertaining to the daily duration of rain. While table 47 showed that the over-all effect of seeding on the daily duration of rain was an increase of 18 per cent, significant at 1.8 per cent, in the group of days when the clouds are more amenable to seeding, i.e., when the modal cloud-top temperatures are either in the range of -15° to -21°C, or -11 to -21°C, the effects are larger and more significant. Thus the positive corresponding effects on the

Table 48. Results of seeding on the daily duration of rainfall in the Lake Kinneret Catchment and Control Areas

| Temp. Interval | No. of Days | | Mean seeded | | Mean unseeded | | DR | (SE) | Significance level | |
|---|---|---|---|---|---|---|---|---|---|---|
| (°C) | S | US | LKC | Control | LKC | Control | | | Randomized (%) | (WMW) |
| | | | (hrs./24 hrs.) | | (hrs./24 hrs.) | | | | | |
| T < - 26 | 49 | 38 | 2.30 | 1.83 | 2.84 | 2.22 | 0.986 | (.163) | 52.4 | 44.2 |
| T < - 21 | 70 | 52 | 2.57 | 1.91 | 2.83 | 2.12 | 1.009 | (.129) | 49.1 | 36.4 |
| -26 < T < - 21 | 21 | 14 | 3.20 | 2.10 | 2.82 | 1.85 | 1.000 | (.202) | 48.8 | 24.5 |
| -11 < T | 27 | 21 | 2.67 | 1.85 | 1.61 | 1.26 | 1.126 | (.213) | 30.7 | 22.6 |
| -15 < T | 45 | 38 | 2.46 | 1.66 | 2.27 | 1.92 | 1.247 | (.156) | 8.3 | 17.2 |
| -26 < T < - 11 | 59 | 53 | 2.92 | 1.82 | 2.90 | 2.40 | 1.327 | (.122) | 0.6 | 0.2 |
| -26 < T < - 15 | 41 | 36 | 3.27 | 2.01 | 2.80 | 2.22 | 1.289 | (.147) | 5.1 | 0.2 |
| -21 < T < - 11 | 38 | 39 | 2.70 | 1.66 | 2.93 | 2.60 | 1.469 | (.153) | 0.6 | 0.2 |
| -21 < T < - 15 | 20 | 22 | 3.33 | 1.92 | 2.79 | 2.46 | 1.531 | (.208) | 2.2 | 0.1 |

Notes:

S = seeded, US = unseeded, LKC = Lake Kinneret Catchment Area;
DR= double ratio, SE = standard error, WMW = Wilcoxon-Mann-Whitney non-parametric test.

Data from recording rain gauges.

daily duration of rain are 53 and 47 per cent. These effects are significant at levels of 0.1 and 0.2 per cent correspondingly. Here again the same pattern of the breakdown of the results is repeated: on days when the clouds are either warmer than -10°C or colder than -21°C, the effects are not significant or nil.

We therefore tend to draw the conclusion that, while an over-all increase in daily rainfall in the LKC of 25 per cent may be brought about, partially, by an increase in rain duration of 18 per cent, in the case of the days with the more amenable clouds (those with modal cloud-top temperatures of -15° to -21°C), percentage increases in rainfall are brought about by the same percentage increase in the duration of daily rainfall, i.e. 53 per cent increase in rainfall is obtained by 53 per cent increase in duration or 45 per cent increase in rainfall is affected by a 47 per cent increase in duration respectively.

An examination of table 49, relating to the effect of "static" mode seeding on the daily number of rain periods reveals a remarkable result. As stated above, while the over-all effect of seeding is suggestive of a possible positive effect on the number of rain periods of the order of 15 per cent, the significance level of this result is fairly low, i.e., 17.5 per cent, to the extent that it casts serious doubts on whether there is an over-all effect at all. However, by scanning the last two columns of table 49, pertaining to the significance levels of the various stratifications of the data according to cloud-top temperatures, it can be seen that the only days in which there was a significant (i.e., $<$ 5 per cent) effect of seeding on the number of rain periods, are those which are characterized by modal cloud-top temperatures warmer than -15°C or -11°C.

Since every rain period, or event, is indicative of the passage of a rain cloud over the rain recording station, the results confirm very strongly the postulate regarding the effect of "static" seeding in the initiation of rain in clouds that are on the verge of producing rain i.e., with tops warmer than -11 to -15°C, and yet they cannot precipitate naturally as they are deficient, naturally, of ice crystals capable of growing to the size of graupel particles. Thus the introduction of seeding agents having nucleation threshold temperatures of about -5°C to -8°C will result in the formation of graupel particles and hence will also result in the initiation of rain, which will reach the ground from clouds that otherwise would not have precipitated naturally. The fact that in clouds with colder temperatures this effect is non-existent is, obviously, due to the ability of these clouds to initiate rain by virtue of their greater depths.

In conclusion, it can therefore be stated that static seeding is capable of initiating rain in shallower clouds with tops warmer than -11°C to -15°C and also in increasing rain from clouds with intermediate summit temperatures of -15° to -21°C by primarily increasing their duration as precipitating entities.

Table 49. Effect of "static" mode seeding on the daily number of rain periods in the Lake Kinneret and Control Areas

| Temp. Interval ($^oC$) | No. of Days S | No. of Days US | Mean seeded LKC (No. of rain periods) | Mean seeded Control | Mean unseeded LKC (No. of rain periods) | Mean unseeded Control | DR | (SE) | Significance level Randomized (%) | Significance level (WMW) |
|---|---|---|---|---|---|---|---|---|---|---|
| $T < -26$ | 49 | 38 | 5.88 | 12.02 | 6.93 | 9.39 | 0.633 | (.320) | 88.9 | 39.0 |
| $T < -21$ | 70 | 52 | 6.89 | 12.59 | 7.30 | 10.02 | 0.751 | (.270) | 83.1 | 34.3 |
| $-26 < T < -21$ | 21 | 14 | 9.25 | 13.94 | 8.33 | 11.74 | 0.935 | (.494) | 53.4 | 16.4 |
| $-11 < T$ | 27 | 21 | 5.53 | 6.08 | 3.37 | 8.97 | 2.422 | (.498) | 4.8 | 3.5 |
| $-15 < T$ | 45 | 38 | 5.82 | 5.72 | 4.72 | 10.19 | 2.188 | (.356) | 1.4 | 3.6 |
| $-26 < T < -11$ | 59 | 53 | 8.08 | 11.24 | 6.50 | 10.36 | 1.145 | (.272) | 30.7 | 8.3 |
| $-26 < T < -15$ | 41 | 36 | 8.88 | 13.92 | 6.51 | 9.72 | 0.953 | (.319) | 56.7 | 36.4 |
| $-21 < T < -11$ | 38 | 39 | 7.44 | 9.75 | 5.84 | 9.86 | 1.286 | (.318) | 22.9 | 7.3 |
| $-21 < T < -15$ | 20 | 22 | 8.49 | 13.90 | 5.36 | 8.44 | 0.963 | (.402) | 52.7 | 10.9 |

Notes:

S = seeded, US = unseeded, LKC = Lake Kinneret Catchment Area;
DR= double ratio, SE = standard error, WMW = Wilcoxon-Mann-Whitney non-parametric test.

Data from recording rain gauges.

An interesting question, from both the cloud physics and hydrological points of view is the effect of seeding on the daily means of rainfall intensity. In order to be able to respond to this question there is a need to do the reduction of intensity of each rain event directly from the charts of the recording rain gauges. This is a tricky and difficult task which can result in large inaccuracies due to the inability to measure the slope of the curve delineating the accumulation of rainfall on the chart. Table 50 constitutes an attempt to obtain a rough approximation of the estimated effect of seeding on "rain intensity" by using daily averages of the ratio of daily recorded rainfall divided by the daily duration of rain. Daily means for the LKC and the Control for all stations in both areas for all days of Israeli II, seeded and unseeded, are given in table 50.

Table 50. Estimated effect of seeding on "rain intensity" in Lake Kinneret and Control Areas

| Parameter | Mean seeded | | Mean unseeded | | Significance (%) | |
|---|---|---|---|---|---|---|
| | LKC | Control | LKC | Control | Randomized | WMW |
| Rainfall Intensity (mm/hr) | 3.50<br>(3.64) | 5.22<br>(5.32) | 3.14<br>(3.14) | 4.16<br>(4.36) | 78.4<br>(71.2) | 43.9<br>41.8 |

Notes:

1. Recording rain gauge data pertaining to "Average Rainfall Intensity" as defined in the text.
2. The numbers in parentheses refer to days allocated to seeding and actually seeded.

As can be seen, "rainfall intensity", according to the above definition, has not been affected by seeding.

(d) The effect of dispersion of seeding material on target area rainfall

"Static" cloud seeding as a technique for inducing microphysical effects aimed at rainfall increases, calls for the introduction in the treated clouds, of moderate ice crystal concentration which should be, optimally, of the order of 10 - 30 per litre, depending on the properties of treated clouds. The delivery of the seeding material and its subsequent transport, must therefore be designed to produce such required concentrations at the time and place in the clouds as specified by the above-mentioned physical hypotheses.

In both Israeli I and II, cloud seeding was performed by broadcast, air-borne patrol seeding at cloud base altitudes along lines up wind of the target areas. Figure 35 displays the transport and dispersion pattern under typical wind conditions, as calculated by assuming that the seeding aircraft are moving point sources, represented by short line segments of equal length emitting plumes which diffuse according to models developed by Gagin and Aroyo (1985). As can be seen, the areas between 20 and 50 km are exposed, to concentrations $>10$ $lit^{-1}$ of AgI particles active at $-15^{o}C$, for more than 50 per cent of the time. Other areas either close to or further away from ths area of maximum effect seem to have significantly reduced exposures to such concentrations. It should be recognized, however, that while this method does not affect the whole target area uniformly, it has the great advantage of providing more time for the dispersal and dilution required for "static" effects, to take place in the free atmosphere, prior to activation of AgI particles in the clouds.

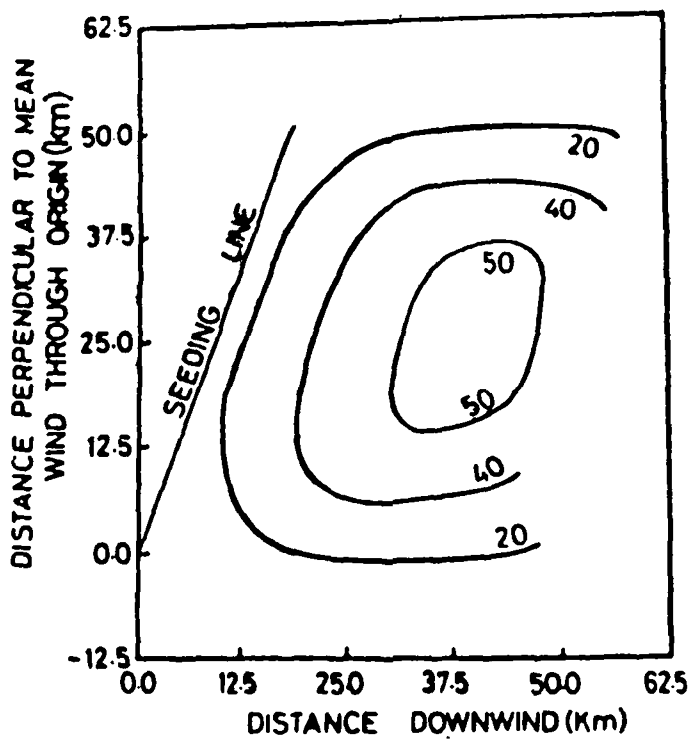



Figure 35. Transport and dispersion pattern for cloud seeding under typical wind conditions

One of the salient results of both of the Israeli experiments, is the detection of area of maximal rainfall increases, under seeding, at a distance of about 20 to 50 km downwind from the line of seeding (Gabriel, 1970; Gagin and Neumann, 1981).

While in Israeli I seeding off-shore resulted in a rainfall increase of about 24 per cent, significant at less than 1 per cent, at distances of 20 to 50 km downwind from the westerly line, in Israeli II the shift in the line of seeding eastwards, inland, aimed at affecting the more eastern catchment area of Lake Kinneret, resulted in a corresponding shift of the area of maximum effect of seeding eastward by a distance comparable to the shift of the line of seeding. In this area an increase of 18 per cent, significant at 1.7 per cent, was recorded. Thus again the statistical results pertaining to the area distribution of the effect of seeding, are physically plausible in that they reflect the diffusion pattern of the seeding materials produced by a seeding technique aimed at producing static effects in clouds in that area.

(e) Concluding remarks on "static" mode seeding

The present study constitutes another confirmation of the results of Israeli II, with regard to the effect of seeding in the LKC, as it is based on a totally independent data set of rainfall measurements. Its main contribution to the acceptability of the results of this experiment is in that it provides an additional component of the already accumulated evidence pointing to the physical plausibiity of the statistical findings of both Israeli I and II. The verification of the basic working assumptions outlined at the outset of the Israeli rainfall enhancement experiments, namely, that static seeding will enhance rainfall either by making the already existing rain mechanisms more effective or by the initiation of rain in clouds that otherwise would not have precipitated, adds more strength to statistical results indicating signficant overall rainfall increases. It also confirms the basic postulates, forming the basis for the theory of "static" cloud seeding for rainfall enhancement, that microphysical effects are produced in continental clouds, which characteristically are stable colloidal entities requiring the ice crystal-riming graupel processes as a necessary condition for rain formation.

## 3. Evaluation of the basic tenets of "dynamic" seeding as inferred from an analysis of FACE 2

The Florida Area Cumulus Experiment (FACE) was a two-stage programme to investigate the potential of seeding for dynamic effects for enhancing convective rainfall in a fixed target area in South Florida. The first stage, or exploratory phase (FACE 1, 1970-1976) produced substantial indications of increased rainfall in the target area (Woodley and others, 1982). The second, or confirmatory phase (FACE 2, 1978-1980), did not confirm the results of FACE 1, although it did produce indications of a possible seeding effect (Woodley and others, 1983).

As specified by Woodley and others (1978), the FACE 2 programme was designed to have an ambitious exploratory component in order to obtain better physical insights into the effects of seeding. A major component of the

FACE 2 exploratory studies is the volume scan radar programme. The radar-volume-scan (RVS) technique which was developed specifically for these studies has been described in detail by Gagin and others (1984). The major objective of that study was to provide a more detailed scientific basis to the theory of rainfall enhancement by seeding for dynamic effects (see Woodley and others, 1982 for discussions of "dynamic" seeding). The basic tenet of dynamic seeding is that the production of a taller cloud results in more rainfall. While previous studies by Simpson and others (1967), Dennis and Koscielski (1972) and Gagin (1980) have all shown that deeper convective cells produce more rain, the study by Gagin, Rosenfeld and Lopez (1984) was aimed at demonstrating that the larger rain volumes precipitated by deeper convective cells are due to the larger area, longer rain duration and stronger rain rates of these cells.

(a) Methodology of radar volume scan observations

The details of the methodology for observing the evolution of convective rain cells by the radar volume scan techniques have been given in Gagin and others (1984a). The following is only a résumé describing in general terms this technique.

The determination of the relationship between the vertical dimension of convective cells and their other basic properties such as area, intensity, and duration requires the collection of extensive observations of cell characteristics, such as can be obtained by radar volume scanning techniques, and the use of suitable analysis procedures capable of tracking these cells throughout their lifetimes. Digitized radar with adequate data recording facilities are required for data collection and high speed, large memory computers are needed for its subsequent analysis.

The studies were carried out in South Florida within the framework of the research conducted in FACE and were performed by the use of two different but virtually colocated radar systems. The first was a WSR-57 S-Band radar operated by the National Hurricane Center, and the second was an MPS-4 C-Band radar operated by the University of Miami. The latter C-Band radar provided the volume scan data while the former S-Band radar provided the surface rainfall characteristics from low-level scans.

A set of computer programmes was developed to idetnify echoes and the cells within them and to track the cells throughout their lifetimes. In general terms, an echo is isolated by determining a set of contiguous grid elements containing a radar return above the threshold for noise. It is then inspected for radar reflectivity maxima. These maxima are identified and labelled as centres of cells. The total echo area is then divided into the different cells along the lines of minimum reflectivity between the peaks. Grid elements that fall on those lines are assigned to the cell whose peak is closest. On rare occasions the peaks are embedded in a matrix of uniform but lower reflectivity. In these cases the dividing line is drawn midway between the reflectivity maxima.

As defined by the above-mentioned procedure, a cell corresponds to a precipitation area with a distinct maximum. These precipitation areas very often correspond to distinct height features in the echo-top height maps. Echoes larger than about 100 $km^2$ in area tend to have two to several reflectivity and height peaks. This characteristic has been observed since the days of the Thunderstorm Project in Florida and elsewhere and seems to be general property of convective systems (Lopez and others, 1984). These peaks are associated with echo regions that can be tracked back and forth and can be seen to form, reach a maximum reflectivity, decay and eventually dissipate with life cycles generally independent of each other. They also retain their relative positions among themselves and their general configurations from one time period to the next. Lopez (1978) has associated these regions or cells with individual convective elements. Once a convective cell, definable by its surface properties as a rain cell, was identified and tracked throughout its lifetime, the volume scan data were used to provide the maximum vertical dimension ($H_{max}$) as well as its time-height history. In addition, the low-level scan radar provided the maximum and lifetime properties of the rain cell such as its instantaneous and maximum area (A and $A_{max}$) the corresponding values of reflectivity (Z and $Z_{max}$) and cell duration (DUR). The rainfall values R were calculated from the FACE Z-R relationship ($Z = 300\ R^{1.4}$) and these were then used to compute the other integrative properties of the cells such as the rainfall volume rate (RVR) and the total rain volume (RV).

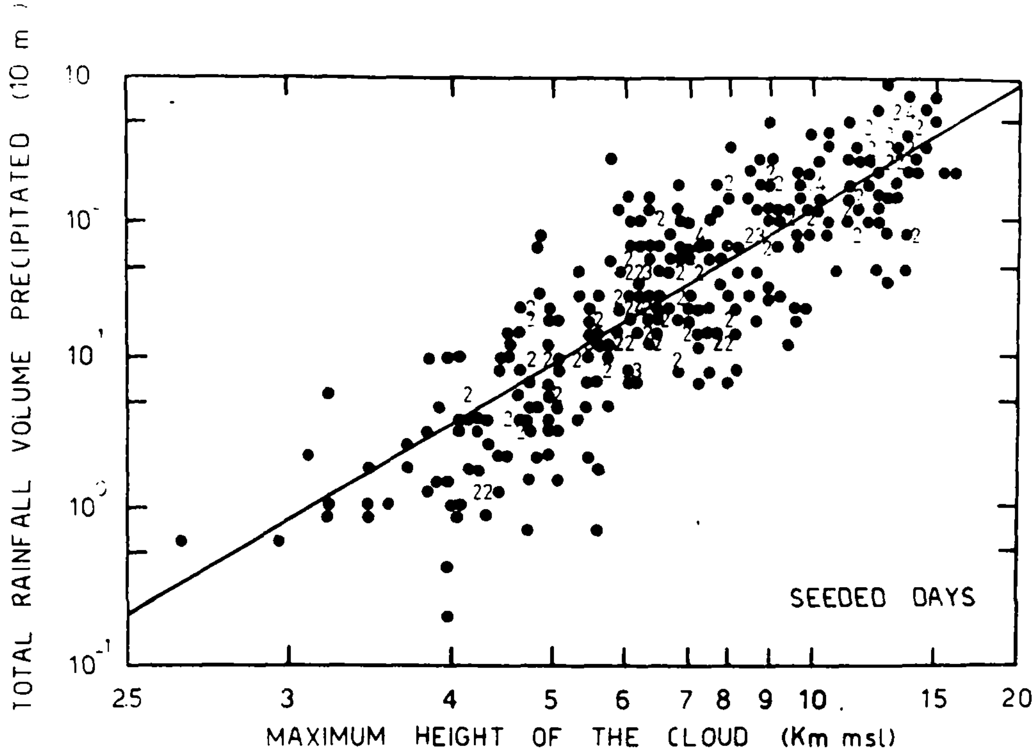
(b) Regression analyses of the data

A total number of 349 "natural" unseeded convective cells were studied and tracked throughout their entire lifetimes during the months of July and August 1979. The cells were all located at distances of between 60 to 100 km from the radar site throughout their existence.

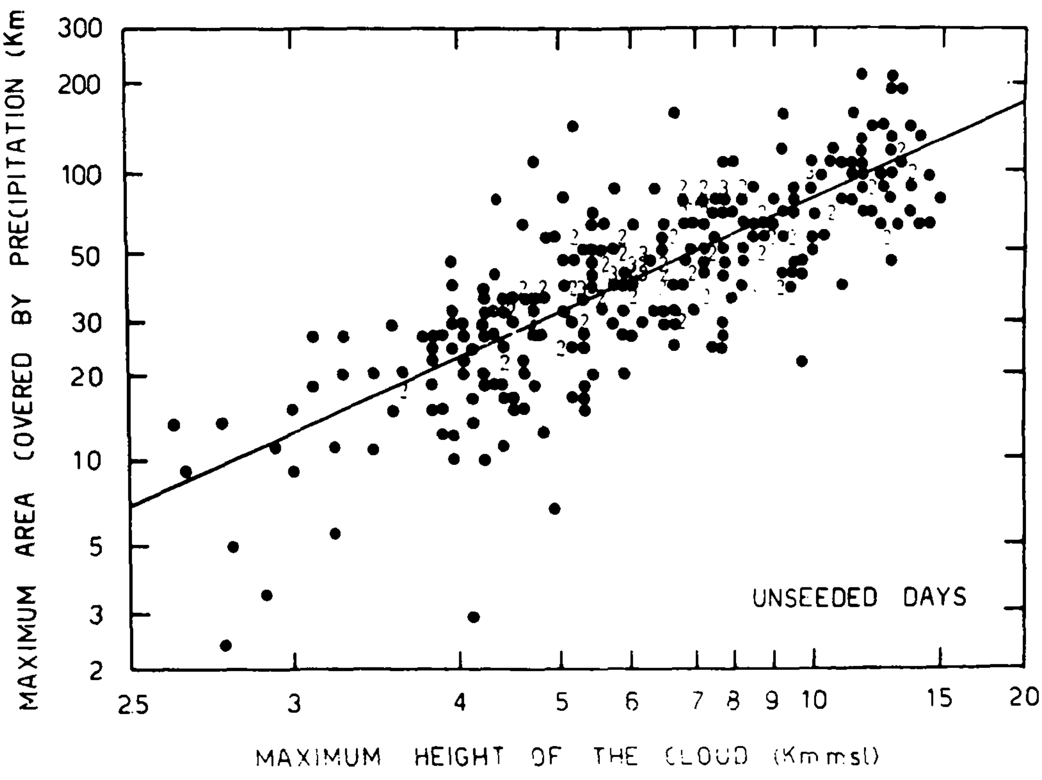
Regression analyses were applied to this data, in an attempt to relate the various above-mentioned maximum lifetime and integrative properties of these cells, to the maximum vertical extent attained by the cells during their existence.

A set of highly correlated relationships which are characterized by a corresponding set of power laws, was found to suggest that indeed taller convective raincells produced larger total rainfall volumes in virtue of their larger precipitating areas, rain rates and rain durations. The power law constants as well as the actual scattergrams are given in Gagin, Rosenfeld and Lopez (1984). Figure 36 displays, for example, the regressions pertaining to the relationships between the maximum heights and the total rain volumes precipitated by seeded and unseeded convective raincells. As can be seen, a two-fold change in maximum cell height corresponds to roughly a factor of ten increase in total rain volume for both types of clouds.

In general terms these results confirm, rather comprehensively, the basic tenet of the theory of rainfall augmentation by cloud seeding aimed at producing "dynamic" effects as hypothesized by Simpson (1971).




a. Seeded days




b. Unseeded days

Figure 36. Relationships between the maximum heights and total rain volumes precipitated by seeded and unseeded raincells

(c) The data and description of the analytical approach

The results and data base for the present summary came from a study performed by Gagin and others (1984), during a total number of 21 days for which both radars were operative to yield echo volume and surface reflectivity data. Four of these days were observed during the 1979 field season and the other 17 were from the 1980 field season. Unfortunately, all other FACE 2 days (A and/or B days) could not qualify for this study because of technical difficulties either in recording the data or in the operation of the MPS-4 radar. Out of the 21 days, only 3 days enter the category of "A" days ( $<$ 60 flares expended due to poor weather conditions); the rest fall in the category of "B" days ( $>$ 60 flares expended). Only category "B" days were used in this study.

A total of 2,369 convective cells between 60 and 100 km from the radar have been studied on the 18 "B" days; 2,069 cells were found to be untreated and 300 cells were treated with either AgI or sand (placebo) flares. This relatively small number of treated cells is due to the narrow annulus (i.e. 60 to 100 km) in which cells were studied and to the strict criteria for seeding which were applied during the experimentation (see Barnston and others, 1983). In any case, since this study is dealing with the effects of seeding on single cells (the experimental unit), the numbers quoted above seem to ensure a sufficiently acceptable data base.

Once the seeding decisions were known, all clouds were stratified into four different groups:

(i) Clouds that had been treated with at least one AgI flare during their lifetime (TAgI);

(ii) Clouds that had not been treated on days when AgI seeding was applied (cAgI);

(iii) Clouds that had been treated with at least one of the sand (placebo) flares during their lifetime (Tsand); and

(iv) Clouds that had not been treated on days when placebo flares had been employed (Csand).

Special, stringent criteria were applied to the potential control cells in order to qualify them for inclusion in the study. An acceptable, untreated control cell is either one that forms within 20 km of the centre of the treated cell and 30 min before or after its initial seeding or one that forms any time at least 20 km from the centre of the treated cell. Despite these selection criteria, it was noted that the daily mean properties of all control cell properties were correlated with the corresponding properties of the treated cells on the sand-treated days. This provides justification for the use of the control cells in the evaluation to be described below.

Taking note of the fact that the treated clouds were selected for treatment, it would be natural to assume that they are biased (whether treated with AgI or sand) with respect to all other untreated clouds, which were not selected for treatment either because they did not qualify, or because the limited number of seeding aircraft could not cope with all available treatable clouds. Nevertheless, untreated cells can be used as internal controls as a means of reducing the day-to-day variability or bias. Thus, if one could guarantee that on all days, relatively equal proportions of treated and untreated control cells could be selected, then the Double Ratio estimate of seeding effect could be utilized to compensate for this bias:

$$DR = \frac{(\quad)\,TAgI}{(\quad)\,CAgI} \times \frac{(\quad)\,Csand}{(\quad)\,Tsand} \qquad (2)$$

where the values in the parentheses can be the mean of any of the following lifetime properties of the clouds: $Z_{max}$, $H_{max}$, $A_{max}$, RV, $RVR_{max}$ and DUR. The suffixes that relate the clouds to the various four groups have been defined earlier.

If DR exceeds the value of one, it would be an estimate of the effect of seeding on the particular parameter under study. Again, it must be emphasized that the DR estimate can be used only if the right hand ratio of equation (2) compensates fully for the bias introduced by the selection of the cloud and if the sample size is representative of the four groups. The use of the DR can be applied of course on any sub-set of the total data base. It was used primarily for an over-all estimate of the seeding effect per cloud by pooling all days together and subsequently subdividing the total cloud population into four groups as desecribed above.

In addition to the use of the Double Ratio, use was made of the Single Ratio (SR), see equation (3), for the estimation of AgI treatment. Obviously SR lacks the compensation for day-to-day variations if they occur. Its use is therefore limited by the assumption that, in the long run, if seeding had no effect, SR should have attained the value of unity.

$$SR = (\quad)T_{AgI}/(\quad)T_{sand} \qquad (3)$$

(e) Results

A listing of the dates used in the study and the treatment decisions is provided in Gagin and others (1984). The relationships between the maximum vertical dimensions of the cells and their other lifetime properties for both AgI- and sand-treated days, are given in table 51. As can be seen from this table, these relationships are not only well correlated but the AgI and sand relationships are practically the same.

The similarity of the sand and AgI regressions for all cell properties has two possible interpretations:

(i) There is no effect of AgI treatment; or

(ii) There may be an effect of AgI treatment which results in taller clouds that behave as taller natural clouds, or, in others words, the effect of seeding may be to move the points upwards along the regression lines. The possibility is investigated next using the single and double ratios as defined earlier.

Table 52 provides mean cell properties for the four categories

Table 51. Relationship between the maximum "depth" and other properties of convective cells on sand-treated and AgI-treated days

| Regression between: | No. of cells | | Regression coefficients: Slope | | Intercept | | Correlation coefficient | | Standard error of estimate | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Sand | AgI | Sand | AgI | Sand | AgI | Sand | AgI | Sand | AgI |
| Log $A_{max}$ and log $(H_{max}-h)$ | 349 | 385 | 0.97 | 0.92 | 1.02 | 1.01 | 0.79 | 0.77 | 0.19 | 0.18 |
| Log $Z_{max}$ and log $(H_{max}-h)$ | 349 | 385 | 2.20 | 2.33 | 2.68 | 2.45 | 0.78 | 0.78 | 0.46 | 0.44 |
| Log $RVR_{max}$ and log $(H_{max}-h)$ | 349 | 385 | 2.14 | 2.20 | 0.82 | -0.65 | 0.84 | 0.84 | 0.35 | 0.34 |
| Log DUR and log $(H_{max}-h)$ | 349 | 385 | 0.60 | 0.70 | 1.00 | 0.84 | 0.59 | 0.66 | 0.14 | 0.15 |
| Log RV and log $(H_{max}-h)$ | 349 | 385 | 2.44 | 2.63 | -0.02 | -0.28 | 0.84 | 0.85 | 0.40 | 0.39 |

Table 52. Means, single ratios and double ratios for the various cell properties, on 18 "B" days of FACE 2

| Cell property | $T_{AgI}$ | $C_{AgI}$ | $T_{sand}$ | $C_{sand}$ | SR | DR | Rerand SL (%) SR | DR |
|---|---|---|---|---|---|---|---|---|
| Rv $[10^3 m^3]$ | 200.6 | 83.1 | 175.3 | 104.0 | 1.14 | 1.42 | 25.4 | 4.2 |
| $Z_{max}$ [dBz] | 44.9 | 38.5 | 44.4 | 39.9 | 1.01 | 1.05 | 25.5 | 4.0 |
| $H_{max}$ [Km] | 9.1 | 8.0 | 8.6 | 8.1 | 1.06 | 1.07 | 19.6 | 10.0 |
| $A_{max}$ $[Km^2]$ | 75.8 | 59.6 | 74.5 | 60.3 | 1.02 | 1.03 | 40.0 | 38.0 |
| $RVR_{max}$ $[10^3 m^3 h^{-1}]$ | 616.2 | 320.1 | 612.6 | 393.1 | 1.01 | 1.24 | 47.8 | 12.1 |
| DUR [min.] | 34.1 | 23.4 | 32.3 | 23.9 | 1.06 | 1.08 | 20.0 | 18.4 |
| n | 161 | 1066 | 139 | 1003 | | | | |

Note: The significance levels (SL) were obtained by 3,000 rerandomizations of the data.

($T_{sand}$, $C_{sand}$, $T_{AgI}$, $C_{AgI}$) for all treated cells regardless of amount of treatment within the annulus 60 to 100 km from the radar on the 18 "B" days (9 AgI treated and 9 sand treated) of FACE 2. This table also provides the double ratio (DR) and the single ratios (SR) as defined above. The significance levels were obtained by the Monte Carlo rerandomization technique (3,000 iterations).

There are several items of interest in table 52. Note first that in every instance the control cells have smaller means than the means for the treated (either AgI or sand) cells. This difference is not surprising since the best clouds were selected for treatment. Nevertheless, the properties of these control cells are strongly correlated (correlations ranging between 0.57 and 0.85 on sand-treated days) on a day-to-day basis with the corresponding properties of the treated cells and can, therefore, be used validly as internal controls.

A second item of interest in table 52 is the finding that the properties of the control cells on AgI days are somewhat smaller than the corresponding properties of the control cells on sand days (this disparity is greatest for cell rain volumes to which rain rate, area and duration contribute in a multiplicative fashion). This could be due either to chance or to suppression of the control cells on AgI days by compensating currents around the AgI-treated cells. Acceptance of the latter possibility, however, means necessarily acceptance of the premise that AgI seeding has enhanced the growth of the treated cells.

Evidence for an over-all effect of AgI seeding in terms of the double ratio is strongest for cell rain volume and for maximum reflectivity, but because of the imbalance between control cells on sand and AgI treated days, it is not clear what interpretation should be given to this result. The indicated effect in terms of the single ratio, although smaller, is still greater than one, so an overall effect of seeding is still indicated.

The over-all results are suggestive of an effect of seeding but the evidence is rather weak. Greater physical insight is obtained by partitioning the data based on the amount of material (AgI or sand) injected into the cloud and on the stage of the cell life cycle at which the treatment took place.

The results as a function of flare expenditure (70 g, AgI) suggest a positive effect of treatment that is strongly dependent on the amount of nucleant introduced in the cells. For example, no effect on total rain volume is indicated for cells receiving four flares (i.e., less than 280 AgI or 400 g of sand) but a strong and significant effect is indicated for cells that received more than nine flares (i.e., more than 630 g of AgI or 900 g of sand).

Further physical insight into the effect of seeding is obtained by partitioning the results based on the stage in the life cycle of the cell at which seeding took place. Throughout FACE, it has been specified that it is most desirable to seed the supercooled clouds when they are young and vigorous with strong updrafts and much of the liquid water near the cloud top (see Woodley and others, 1982; Woodley and others, 1983). In such situations the cell has been producing a radar return for only a short time.

Thus, there is a solid physical basis for partitioning the results by life cycle as shown in table 53. This table summarizes the mean properties of only those cells which were treated with at least one flare within five minutes of their first appearance on 5-band radar. It can be noted that the size of the apparent effect of treatment is large and significant for all cell properties as would be expected since, as a population, these cells had to have been the most suitable for treatment.

Cells that were treated later in the life cycles when they were undoubtedly less suitable than their younger counterparts for seeding showed virtually no effect from seeding, even with large flare expenditures. Microphysical studies have shown that, once the subject clouds reach the -10°C seeding level, natural glaciation is often complete within 10 minutes. This underscores the importance of timing when conducting dynamic seeding experiments.

(f) Discussion of the results

The evidence is strongly supportive of dynamic seeding concepts as applied to individual convective cells. As stated repeatedly throughout FACE and as verified by Gagin and others (1984), the height of a convective cell is a predictor of its other gross rainfall properties. By manipulating cell height one can reasonably expect to manipulate cell rainfall area, intensity and duration and, hence, total cell rain volume. This summary suggests that by seeding with large amount of nucleant early in the life cycle of Florida-type rain cells, it is possible to increase their heights by an average of 20 per cent and their rain volumes by an average of over 100 per cent as a consequence. This result is strongly supportive of the early single cloud studies reported by Simpson and Woodley in Florida. Strong evidence has been presented that seeding effects are limited to the cells that were treated early in their lifetimes. This result can be explained by microphysical studies in Florida that indicate that individual cells remain suitable (i.e. high water contents and strong updrafts) for only a short time. In view of the critical nature of the timing of seeding, treatment of a broad tower with a small number of flares is not likely to be effective, because the time necessary to diffuse the nucleant throughout the tower may well exceed the period of time during which the tower is suitable.

A last matter of importance is the question of whether the control clouds in the vicinity of the AgI-treated clouds were suppressed by the invigorated seeded clouds. The data suggest that this might well have been the case since the control cells on the AgI days were weaker and less rain-productive than the comparable control clouds on the sand days. Here again, however, one cannot be certain that this control cloud disparity was not produced by natural causes. In other words, the luck of the draw might have dictated wetter sand days. Fortunately, this is a no-lose situation for those arguing for an effect of AgI seeding. Acceptance of the argument that AgI seeding suppressed the nearby control clouds is also acceptance of an effect of seeding. Acceptance of the argument that the draw favoured the sand-treated days is also acceptance of an effect of seeding since its magnitude is increased when accounting for the natural biases.

Table 53. Means, Single Ratios and Double Ratios for the various properties relating to cells which have been treated within 5 min. of their initial appearance on the radar screen

| Cell property | $T_{AgI}$ | $C_{AgI}$ | $T_{sand}$ | $C_{sand}$ | SR | DR | Rerand. SL (%) SR | DR |
|---|---|---|---|---|---|---|---|---|
| RV $[10^3 m^3]$ | 248.9 | 83.7 | 157.2 | 104.0 | 1.58 | 1.97 | 4.4 | 1.8 |
| $Z_{max}$ [dBz] | 46.4 | 38.5 | 44.3 | 39.9 | 1.05 | 1.09 | 1.8 | 1.2 |
| $H_{max}$ [km] | 9.7 | 8.0 | 8.6 | 8.1 | 1.13 | 1.15 | 8.8 | 3.3 |
| $A_{max}$ $[km^2]$ | 82.4 | 59.6 | 72.4 | 60.3 | 1.14 | 1.15 | 11.8 | 6.5 |
| $RVR_{max}$ $[10^3 m^3 h^{-1}]$ | 759.6 | 320.1 | 598.2 | 393.1 | 1.27 | 1.56 | 9.1 | 3.5 |
| DUR [min.] | 32.2 | 23.4 | 27.9 | 23.9 | 1.15 | 1.18 | 14.6 | 12.7 |
| n | 68 | 1066 | 52 | 1003 | | | | |

Notes:

1. Data collected on the 18 "B" days of FACE 2.
2. The significance levels (SL) were obtained by 3,000 rerandomizations of the data.

g) Concluding remarks on "Dynamic" mode seeding

The findings of the above-quoted recent studies suggest that AgI seeding in FACE 2 affected the properties of the treated convective cells and the resulting total rainfalls and that the changes in these properties were predicted from the changes in cell height following seeding. The effect of seeding appears to be strongest for cells treated early in their life cycle with a substantial amount of AgI (i.e., more than 600 g). Seeding effects of a 20 per cent increases in cell height and over 100 per cent increases in cell rain volume are indicated. These substantial effects have been found to be probably associated with a parallel suppressive effect on adjacent clouds as a result of dynamic compensating processes resulting from the enhanced growth of the treated convective cells.

Direct experimental evidence now confirms the basic tenet of the technique of rainfall enhancement by cloud seeding for "dynamic" effects. This evidence substantiates the hypotheses that if seeding could increase cloud depth, then the corresponding properties of the deeper clouds, namely their intensity, area and duration of rainfall, will be such that they will precipitate larger total rain volumes. The above-mentioned components, contributing to the total rainfall volume precipitated by convective rain cells, have a dependence on cloud depth in a manner that can be described by a set of power laws. The combined effect of the dependence of these convective rain cell properties on cloud depth is also manifested in a power law relationship which relates a ten-fold increase in total rain volume to a two-fold change in cloud depth.

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## VI. RAIN-WATER HARVESTING: AN OVERVIEW

By Peter Hadwen*

### Introduction

In the first instance, the expression "non-conventionl water resources use" appears to cover the treatment and use of water that was previously considered unusable or unavailable, and applies to the physical situation. Secondly, the notion that providing the water is technically more complicated in development and operation than conventional sources to some degree justifies calling the process non-conventional. Thirdly, the same is true if the cost of the water exceeds $\$0.25/m^3$. In large measure, these three definitions relate to the economics of turning unusable or very distant water into a viable supply. However, the most widely held understanding of the state of being conventional or otherwise refers to attitudes of mind, that is, the current inclination of water resources developers, communities served, and agencies investing in overseas development assistance. It might otherwise be called fashion, and there are implied elements of technical innovation, judgement and appropriateness.

Rain-water harvesting has been practised for more than 4,000 years, and in the sense of treating and using water that is already available, it is completely conventional. So much so that for those who seek more than basic human needs of water, it has for some years been regarded as an old-fashioned and out-dated kind of water supply. This conferene has seen massive promotion for desalination, and to a lesser degree for marine transport of water. For those living in coastal areas and islands, especially in the arid zones, the interest is readily understandable. However, those technologies do not have global application, and there are rather large differences of scale and priority. Would we be accurate in thinking that about 50 million people benefit from the supply of desalinated water, in many cases piped to their homes? Would we also be accurate in estimating the number of people having no regular water supply as 2,000 million? For these desperate 2,000 million or more, living in interiors of continents, rain-water harvesting represents the only viable form of water supply.

The use of rain-water harvesting is necessary in areas having significant rainfall but lacking any kind of conventional centralized government supply system, and also in areas where good quality fresh surface or ground water is lacking.

This paper reviews the present extent and manner of collection and storage of rain water from roofs and purpose built collecting surfaces. In a parallel paper, a summary of Caribbean small island experience is given, from which it is noted that at least 750,000 of the people on those islands depend at least partly, and in many cases wholly, on such supplies.

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The author's interest in the subject began in 1975 when it became clear that the runways of Nassau International Airport (Bahamas) would yield 400 million gallons (100 million/$m^3$) in an average year. At that time computer print-outs obtained from several major libraries listed only 27 references for the entire field of rain-water collection. One of these references contained the following quotation: "People living in remote areas of developing countries believe that rain water is the cleanest. Tap water is considered to be second class. The problem of using rain water (in Thailand) is that water falls during a certain period of the year only". The paper contained a water balance study for one roof and found that quantities in storage were acceptable, and of good quality, and that roof collection was viable. Admittedly, coliform counts were high, but were much lower than in water taken from ponds and rivers (Pinkayan, 1973).

The author's United Nations project activities led him to examine rainwater collection in the Bahamas and the following facts emerged:

(1) In more than 20 islands, roof catchments were the only form of water supply, occasionally supplemented by wells.

(2) A completely reticulated system based on ground and roof catchments served one community.

(3) A major rum manufacturer caught and used water derived from factory sides and roof runoff.

(4) From owners of older houses having roof catchment systems, an entrepreneur bought water for a few cents per gallon, de-ionized it, and sold it for $1.20 per gallon.

(5) Former or existing military bases depended entirely on 3-4 acre concrete or asphalted catchments, including runways.

(6) The water needs of an entire condominium were met from roof catchments.

(7) The taste, colour and odour were much preferred to government water supplies.

At a United Nations seminar held in Barbados (Hadwen, 1980) on Small Island Water Problems, one whole session was devoted to rain-water harvesting, and many islands' experience became documented, notably that of Bermuda. What also became apparent was that much documentation was unpublished.

The interest in rain-water harvesting was shared by others, and this climaxed in 1982 at the first International Conference in Hawaii, when 50 papers were read (Fok, 1982). A second conference was held in St. Thomas, United States Virgin Islands (USVI) in 1984 (Smith, 1984), and a third will be held in Thailand in 1987.

The interest in the subject quickened; the Water and Sanitation for Health (WASH) projet, supported by the United States Agency for International Development (USAID) released a number of publications including a subject review (Keller, 1982). In a literature review (Latham and Schiller, 1984) 267 entries were listed, only 62 of which predated 1975.

Why this sudden interest within 10 years? One of the main reasons is that many development assistance groups directed their interest to small-scale projects for meeting basic human needs, often with emphasis on community development. Another reason was the changing attitude towards rain-water harvesting: that the high construction costs would be reduced; that water quality could be to WHO standards with minimal treatment; and that it was appropriate to many people's needs. That is to say that rain-water harvesting was technically effective, convenient, acceptable and affordable by the poor. Roof catchments made use of local materials, were easily maintained, and were capable of being upgraded.

### A. Harvesting methods

There are three types of rain-water catchment systems: roof catchments; rock catchments; and, rain-water harvesting, the collection of water from ground surfaces that have been modified in some way to collect water, usually to feed into a storage tank.

Run-off from any surface depends mainly on rainfall intensity. Natural surfaces (soils of hills, valleys and plains) in arid and semi-arid areas dry out under the effect of the sun. Unless rainfall of 0.75 in/day (2 cm/day) over several days occurs, run-off is not generated. Rain is absorbed by the soil and evaporates back into the atmosphere. To make effective and beneficial use of the water, the natural surface needs modifying in some way to reduce or eliminate permeability.

The more important ways to modify the surface are to:

(1) Level and compact by rolling;
(2) Apply chemicals;
(3) Bind the surface to form a seal;
(4) Create a rigid surface such as concrete;
(5) Cover with flexible material such as plastic.

There are various levels of efficiency and cost; clearly the least cost solution is usually sought for. The over-riding issue is that: one inch of rain on an acre amounts to about 23,000 I gallons; 1 cm of rain on 100 $m^2$ of roof yields 10,000 litres.

Compared with surface stream flow or ground-water levels, recovery from drought can be extremely rapid, if a ground level or roof catchment has a high run-off efficiency, and the water is adequately stored.

Present techniques for catchment construction are undergoing scrutiny to decrease costs. The following are desirable characteristics for prepared catchments (Myers, 1974):

(1) Run-off should be non-toxic;

(2) Surface shuld be smooth and impermeable;

(3) Structure should resist weathering and not deteriorate physically or chemically;

(4) Structure need not have great mechanical strength but should be able to resist weather, water flow, plant growth and burrowing;

(5) Materials should be inexpensive on an annual cost basis, and site preparation and construction costs minimal;

(6) Maintenance procedures should be simple and low cost.

In many parts of the world, the use of runways as a collection surface is attractive, especially where present day usage is minor, such as at abandoned military bases. Such water may not be adequate for potable needs, but can be important for agricultural and other non-potable purposes.

Roof catchments are the most common rain harvesting method, and offer the greatest potential for the future because they provide the most convenient and cleanest of all rain-water supplies. With their related storage tank, they can be an expensive means of supply and it is particularly desirable that they be well designed and looked after. If possible, the system size should be related to incidence of drought rather than to normal conditions.

The growing number of galvanized iron roofs, as distinct from straw grass, or palm leaf, is encouraging rain collection in many countries. On the whole, because natural materials attract rodents and insects, often yielding contaminated and coloured water, they are found objectionable as a collecting surface for most people.

Proper design is important; water quality problems may occur and, if they do, they can usually be traced to inadequate design and poor construction. Galvanized iron produces very efficient run-off, approaching 100 per cent in most cases. Unlike plastic, acrylics, concrete, and asphalt, galvanized iron does not decay in the sun. The relatively high temperature derived from the sun's rays is quickly lowered during the quenching first few minutes of rain. Evaporation loss is small, and absorption nil. Tile roofs cool down much more slowly, and are less efficient than metal surfaces Any paint used needs to be non-toxic, tasteless and have low peel/flaking character.

Under corrosive sea spray conditions on small islands, a life of 20 years can reasonably be expected of good quality sturdily-gauged galvanized iron. Inferior materials can last as little as five years under the same conditions, but in areas distant from the sea, have a reasonable life expectancy.

## B. Storage tanks

Especially in the case of domestic supply, it is essential to make the best use of the available run-off at the lowest cost. The cost is directly proportional to tank size; the problem becomes one of maximizing supply while at the same time minimizing storage tank volume. This becomes an awkward question if the area suffers from droughts, and the more wealthy the community, the larger the tank to cover this risk.

For communal as distinct from individual systems, especially in long narrow islands, localized storms may cause some tanks to overflow while others remain empty. A relatively low-cost solution to this is to interlink the reservoirs by a gravity fed or pumped pipeline.

A common container for many people is the 200 litre oil drum. These are cheap and durable, but too small to be more than temporary. One traditional method for a permanent low-cost, easy to excavate tank is to excavate a hole and to line it with concrete. While building regulations make it mandatory to construct such a tank in a number of islands of the Caribbean, the design and cost is prohibitive for many countries of Africa and Asia. Taking into account all components needed in such a system, in the Cayman Islands, it was estimated that costs, including suitable amortization, would range from \$85/1,000 gallons for a 1,000 $ft^2$ roof to \$76/1,000 g for a 3,000 $ft^2$ roof, cisterns being matched in size and in proportion to roof area. Depending on what is included in these cost estimates, others in the Caribbean have quoted much lower figures of \$15 to \$20 per 1,000 g.

Various innovators tried to solve the problem of cost and they have developed above-ground sectional or corrugated galvanized iron tanks, and all kinds of shapes and sizes of fiberglass, plastic, even wood tanks. Plastic-lined earth reservoirs with or without a floating roof have become popular.

On a smaller scale, since about 1980 other designs have included block and ring tanks, and jars, all of concrete. However, the first break-through really started with the development in the early 1950s of the ferro-cement tank. This basically involved erecting an iron form on a concrete base, wrapping it with chicken wire, reinforcing with fencing wire, and plastering with cement. These have been highly successful and durable in Africa, and increasingly are being built in many other areas. They are inexpensive and are easily built by unskilled labour. For some areas of the world, such tanks are still too costly, even with economies of scale and placing the structure in excavated holes. Moreover, even where manpower is plentiful, there may be a traditional resistance in many countries to the labour involved, and to going underground.

In the 1970s experiments using bamboo to reinforce concrete tanks proved highly successful. Smaller concrete tanks or jars using a basket framework were also built, and an exciting new approach to water storage was born founded on:

(1) Community based co-operative work, providing opportunities for people to help themselves;

(2) Mobilizing joint efforts between Government and Non-Governmental Organizations (NGOs);

(3) Choosing technology appropriate to the economic and social circumstances;

(4) Rapid construction: one tank completed in a day.

The kind of tank chosen depends on local factors. However, it is clear that costs are being very much reduced. Figures of less than $100 are quoted for some of the 11 $m^3$ Thai tanks, and it is pleasing to see that similar construction techniques have been successfully introduced in East Africa, where 10 $m^3$ ferro-cement tanks are now constructed at a cost of $100 to $150.

Studies in Thailand have shown that bamboo reinforced water tanks are less cost effective than water jars and construction of dug wells. However, wells are easily contaminated, and jars are too small for many households. Therefore, the Population and Community Development Association (PDA) selected the water tanks as the optimal solution. In several African and Asian countries, combined roof catchments and storage tanks have proved to be financially, socially and economically the most appropriate form of water supply.

### C. Public health and maintenance

The most important consideration is to keep a water system working while at the same time ensuring that quality of the water is as high as possible. Properly designed roof catchment systems produce good quality water; ground-water catchments do not always achieve such high quality standards owing to the difficulty of properly protecting them.

Key maintenance considerations listed by Keller (1982) are as follows:

(1) Any rainwater harvesting system has catchment, channelling, storage and delivering components, which must be given frequent attention;

(2) Roof catchments are not as vulnerable to the human and animal traffic that can cause damage/contamination to ground systems;

(3) A procedure or device for eliminating the "foul flush" after a long dry spell deserves particular attention;

(4) Gutters and down pipes need to be periodically inspected and cleaned carefully;

(5) All tanks need cleaning; their designs should allow for this;

(6) Community systems require community organization for effective maintenance; household systems require a correspondingly smaller scale of organization.

### Conclusion

Whatever the technique, rain-water harvesting works on the principle of intercepting rain as its falls, and then storing it for beneficial use. Preparation of a suitable collection surface and channelling the flow is the relatively easy part.

The construction of a low cost reservoir has presented that greatest challenge, and it is improvements in those techniques that the greatest advances have taken place in the last five to seven years.

Many other low-cost appropriate technology studies have been carried out in the last decade -- gravity supplies, handpumps, shallow wells, sand dams and use of solar and biogas energy sources, to name a few. Problems of remoteness of village or islands, difficulty of obtaining fuel or other supplies, provision of maintenance, high cost and relability, are all relevant issues common to most water supply. If an improved village water supply system breaks down, people resort to traditional sources, such as ponds, water holes, springs, rivers, which are often badly polluted. Thus, any health benefits resulting from their improved supply are often lost during such break-down periods.

By its very simplicity of concept, rain-water collection probably has the most potential for improving water supplies at the level of satisfying basic human needs. In most countries, the full potential rain-water harvesting is not being exploited. In the efforts to meet the ambitious goals of the International Drinking Water Supply and Sanitation Decade, a highly significant role can be played by rain-water harvesting methods.

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## VII. OTHER RELATED TOPICS

### A. Case study for control of boron pollution

by H. Sahin Cengiz*

#### 1. Introduction

Turkey, with an area of 777,000 $km^2$ is located between the Mediterranean and Black Seas. Out of this total area, 27.7 million hectares of land is cultivable. Within the cultivable land, the economically feasible irrigated areas, including major and minor irrigation works, is about 8.5 million hectares and at present there are about 3.2 million hectares of land under irrigation.

The average annual precipitation in Turkey is 652.5 mm and this corresponds to a water potential of 509 billion $m^3$ per year. The average run-off rate is 0.36 and the total run-off is approximately 185 billion $m^3$; 95 billion $m^3$ of the total run-off can be technically utilized. In addition to the run-off water, the amount of ground water available is estimated at 9.5 billion $m^3$. Thus the total available water potential of surface and sub-surface resources amounts to 104.5 billion $m^3$.

As mentioned above, the economically feasible irrigated land of Turkey is 8.5 billion hectares. If the available water were not limited, the amount of land irrigated could be as high as 15 million hectares. However, water quality in some areas is too poor for use in irrigation. Therefore, measures have been introduced to control water pollution and to utilize slightly polluted water for irrigation. A case study has been carried out to control boron pollution in the Simav River and to use that water for irrigation in the north-west of Turkey.

#### 2. Definition of the problem

The Simav River flows from the mid-west of Turkey to the north. There are several irrigation schemes which utilize ths Simav River water for irrigation. In this area 38,000 hectares of land is at present under irrigation, and an additional 30,000 hectares of land will be irrigated in the future. However, there are several borax mines which pollute tha Simav River in the region. The Simav River is now suffering from the boron pollution generated from the Bigadic Borax Mines.

The Bigadic Borax Mines pollute both water and soil in the surrounding area.

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(a) Water resources pollution

The Simav River is polluted by three types of operations carried out at the Bigadic Borax Mines.

First, the borax ore dug from the borax mines is washed at the concentration plant and granulated, producing a highly concentrated substance. However, as a result of this process the rest of the borax deposits, which contain 30 per cent boron, are settled in a simple pool. After settling, this residual in the wash water, containing a high concentration of boron, is discharged to the Simav River.

Second, the drainage water that comes from borax mines contains a high concentration of boron. The result of the analysis of drainage water that was sampled showed that the boron concentration was 200 ppm. The drainage water amounting to 650 $m^3$ per hour was being discharged to the Simav River. This is the main source of pollution. The water samples which have been taken downstream of the Simav River have been analysed and it was found that the boron concentration was about 5 ppm.

Third, the borax sediment stored at the edge of the Simav River is washed by the river water and dissolves some of the borax.

(b) Soil resources pollution

There are two irrigation schemes which were opened to irrigation. The first one is on the Balikesir plain (8,000 hectares) and the other one is on the Susurluk plain (30,000 hectares). These two plains are irrigated with water from the Simav River which has the high boron concentration. The soil samples taken from the Balikesir plain showed that the boron concentration in the soil is as high as 5.2 ppm, which is dangerous for any kind of crops. This high boron concentration has been encountered in the top soil within a depth of 30 cm.

In order to prevent boron pollution of the soil in this area, an economical solution of the problem should be found. Otherwise those two productive plains will become non-productive areas. With this in mind, an intensive study has been undertaken to try to find a solution to the problem, and three different alternatives have been investigated.

## 3. Alternatives and the solution

Three alternatives have been identified to prevent adverse effects on crops from the boron polluted irrigation water.

### Alternative 1. Discharging boron polluted water to the sea by a pipeline

To protect the Balikesir and Susurluk plains from the effects of boron polluted water, the transport of polluted water by a pipeline to the sea has been investigated. The pipeline starts at the borax mines and goes along the Simav River downstream of Yahyaköy dike to the Marmarian sea. The average flow in the pipeline will be 180 litres per second (l/sec). The diameter and the length of the piepline were calculated at 66 cm and 102 km respectively. The investment cost of the pipeline was estimated at US$ 12.6 million.

Alternative 2. Discharging boron polluted water to the sea by a canal

The second alternative is to transport the polluted water to sea by a canal. The polluted water which comes from the borax mines will be collected in a storage pool. The stored water will be discharged downstream of Yahyaköy dike through a canal 156.6 km in length. The flow in the canal is the same as in the first alternative. The total investment cost of the canal system was estimated at US$ 11.5 million.

Alternative 3. Constructing a storage dam for the polluted water

The third alternative is to construct a dam to store boron polluted water during the irrigation period, then discharge it to the Simav River during a short time period (1 or 2 months) after the irrigation season is over. For this alternative a further investigation must be made to determine whether the discharged water would affect the irrigated land or not, because downsteam of the dam another dam has been proposed on the Simav River for irrigation purposes. The water discharged from the Ayitlidere dam may pollute the Susurluk reservoir. Although it is possible that the high spring stream flow of the Simav River will clean the Susurluk dam reservoir, still the reservoir water may contain some boron. The possible boron concentration of the Susurluk reservoir should be estimated. The storage capacity of the Susurluk dam is 250 million $m^3$ and the annual flow of the Simav River is 140 million $m^3$. Seventy per cent of this flow occurs during the winter. This means about 100 million $m^3$ of water comes to the reservoir in winter. This amount of water may decrease the boron concentration in the reservoir before the irrigation season begins. The result of a study on the proposed Susurluk dam operation showed that the average boron concentration would be decreased to 0.2 ppm. This means that the boron concentration in the reservoir would not affect the irrigation water. As a result of this work, the irrigation water taken from the Simav River can be used safely for irrigation if the Ayitlidere dam is constructed to store boron polluted water. The estimated cost of the Ayitlidere dam with a storage capacity of 127.5 million $m^3$ is about US$ 7 million.

## 4. Results and conclusion

A case study has been undertaken to examine alternatives to prevent irrigated areas from being polluted with the boron from borax mines. In this study three different alternatives which would prevent this boron pollution have been investigated. Construction of the Ayitlidere dam seems to be the least-cost alternative in the planning stage.

## B. Appropriate technology for water resources development

by P. Douard*

### Introduction

The importance of appropriate technology in the field of water resources and supply is illustrated by data given by the World Bank:

- In developing countries, at the beginning of the International Drinking Water Supply and Sanitation Decade (1981-1990), 500 million in a world population of 3 billion had enough water, that is to say 20 to 50 litres of water per person per day.

- The cost of providing enough water to the entire world population (China is excluded in these data) is huge. US$ 600 billion was the 1978 estimate, i.e., ten times what was spent by the developing countries on water supply between 1971 and 1980.

- This cost could be halved if appropriate technologies were used.

### 1. What is an appropriate techology?

In dealing with the problem of water supply, planners and engineers need to take a very broad view. They have to think of the economic and human possibilities, to know the geography and geology, and related issues.

An appropriate technology should therefore be:

(a) Cost effective

Most important is the consumer's ability to pay for water. In most developing countries, there are serious constraints to what people can be charged for water; such charges are often directly related to the cost of construction, and to the costs of maintenance and operation, which are almost never subsidized.

(b) Easy to operate and to maintain

Generally, the more complex the technology, the more difficult and costly it is to operate, especially given the shortage of skilled personnel to operate and maintain the equipment. If the chosen technology is too sophisticated, the result will be a loss of realiability through lengthy shutdowns.

These ideas lead us to prefer natural to artificial materials as a basis for appropriate technologies, e.g., use of natural coagulants contained in seeds of ninnali and tamarind trees instead of alum; use of sand filtration instead of activated carbon filters; desalination using aquatic weeds such as water hyacinth.

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However, appropriate technologies are neither old fashioned nor second rate. To illustrate, the research needs identified at the Eighth Conference on Water and Waste Engineering for Developing Countries (Longborough Institute of Technology, 1982) were: improved methods of geophysical exploration; cost effective desalination techniques using renewable energy sources; simplified instrumentation for detection of leaks; feasibility of waste-water reuse; and evaluation of technologies for conservation of water.

These general considerations are well known, even if they are sometimes forgotten. The following is an attempt to illustrate what appropriate technology can be, citing two non-conventional water resources: artificial recharge and leakage control.

## 2. Artificial recharge

Artificial recharge has been identified as the object of experimentation in a project called "Water Resources in North Africa" where aquifers can be recharged with either surface or waste water.

Frouguia, Oued N'fis, located near Marrakesh, Morocco, was chosen as the site for surface water experimentation. In that area, four basins are separated by small embankments of roughly 0.8 m high. From the upper to the lower course of the stream, each tank acts first for infiltration and then for settling. The stored water can be reused for irrigation as well as for the urban needs of Marrakesh. The project was calculated to last 10 years. For the project 150 local labourers worked without mechanical means and the cost was DH 1.16 million[1/] (it would be about DH 0.8 million without the experimentation part). The stored water was 1,250 million $m^3$ with infiltration of 300 to 320 l/s.

Why can this technology be considered as appropriate? According to the above criteria it is seen that it is cost effective, using a local and inexpensive workforce; it is simple to operate and manage, the only needs being maintenance of the basins (142 work days estimated). It is also well suited to this rural area.

The case of Creances, a village situated in Normandy, presents an example of waste-water recharge. As its main products are oysters and carrots, the village cleans its waste water from oyster processing and then reuses it for carrot irrigation.

This was achieved by infiltrating waste water through sand dunes, having first treated it by screening and oil removal (important to prevent clogging).

Remarkable purification results were obtained; the basins are filled with water for 15 days and are then emptied, so that the purification by the soil can be activated by oxygen. After a few days, there remains only a thin layer of dry mud which is easily collected.

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[1/] $US 1.00 = 10.06 Dirhams (International Monetary Fund, International Financial Statistics, 1986 Yearbook. Par rate/market rate, 1985 period average).

This technology is appropriate through its low cost, francs 1.1 million[2] for 600 $m^3$/day and 400 ha. It is easy to operate, and is well adapted to the sandy soils. It could be developed easily on a large scale in North Africa (Tunisia or Morocco).

### 3. Leakage control

Although strictly it is not a non-conventional resource, leakage control must be a cause for concern in every country where water supply is scarce. International funding agencies require reduction of high losses before investing to develop new resources. The economic sense is particularly important where low-cost labour-intensive leakage control systems can be used to defer new capital development expenditures that could be put to better use. In spite of that, in 1975 for example, the unaccounted for water was 46.5 per cent of production in Addis Ababa. In France, similar losses occur, which is why the Seine-Normandy Agency among others, has been working on leakage control.

The basic operations for such control are comparison of production with consumption and clarifying the origin of unaccounted-for water. It can be an overestimation of production, strictly leakage, or waste of water by consumers who are not paying for it. Mapping of the distribution is also important. To locate pipes, there are several possibilities depending on the pipe material.

The methods of leak detection depend on the part of the network concerned. For trunk main leakage, one simple commonly-used method is a by-pass meter, but many other methods are available. Then the leak has to be located through signs of water, chemical tracers or sounding. For water retaining structures, the usual method is to isolate the reservoirs from their supply and to measure changes in the water level. For distribution systems, there are sounding methods, introduction of meters (ultrasound or heat pulse flow meters), pressure measurements and computer methods.

As there is no precise international requirement for leakage control, and as the technologies depend on local conditions (shape of the network, pipe materials), technologies used have a greater chance to be appropriate, and an economical appraisal of a leakage control policy is usually achieved.

In the case of Addis Ababa, three programmes were considered.

(a) Regular sounding comprising a small central loss control data and advisory section, with annual surveys of all consumers' connections and main pipelines;

(b) Intensive sounding alone; and

(c) Intensive sounding and district metering.

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[2] US$1.00 = Fr 8.99 (International Monetary Fund, *ibid*, 1985 period average).

The estimated costs were as follows:

| Programme | Estimated Cost (Birr) | Annual water saved ($m^3$) | Unit cost of water saved (Birr/$m^3$) |
|---|---|---|---|
| A | 101,000 | 634,000 | 0.159 |
| B | 154,000 | 1,269,000 | 0.121 |
| C | 182,000 | 1,903,000 | 0.096 |

Note: $US1.00 = Birr 2.07 (International Monetary Fund, ibid., 1985 period average).

Programme C was chosen for implementation, together with improved meter maintenance, which helped to guarantee that the techniques used were cost effective.

In developing countries, technologies using human work are preferred to more sophisticated techniques. In the case of Addis Ababa, looking for leaks through an inspection during the dry season gave good results. Maintenance is the key for success of a leakage control policy.

## Conclusion

Appropriate technology requires careful thought as it has to be considered in reference not only to a goal but also to the background. The conception phase will be costly, but the first investment will bring further savings.

In conclusion we could quote Gide, a French writer who used to say "...all has already been said. But nobody really listened, so it has to be repeated over and over." That could be true for appropriate technology.

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## C. Dual water systems in the United States Virgin Islands

by Henry H. Smith*

### 1. The Island

The United States Virgin Islands, an unincorporated territory of the United States, is located in the Caribbean Sea approximately 1,100 miles (1,770 kms) east-south-east of Miami, Florida, and 510 miles (821 km) north-east of Willemstad, Curaçao. The U. S. Virgin Islands consist of three main islands and more than 40 smaller islands and cays. The three largest islands are St. Croix, St. Thomas and St. John, with respective land areas of 84, 32 and 19 $mi^2$ (216.3, 82.4 and 49.2 $km^2$). Christopher Columbus discovered the Virgin Islands in 1493 on his second voyage to the New World. After being ruled by several nations, the U. S. Virgin Islands were purchased from Denmark by the United States for defense purposes in 1917 for US$ 25 million.

Sugar cane and cotton were the mainstays of the agricultu.ıl-based economy of the Virgin Islands for most of their history until the late 1800s when agricultural production began a long steady decline. Tourism began to contribute significantly to the economy of the islands in the 1950s, reaching an economic boom in the 1960s. Tourism continues to dominate the economy of the Virgin Islands.

St. Thomas is approximately 19 miles (30.6 km) long and 2 to 3 miles (3.2 to 4.8 km) wide. It is of volcanic origin and most of the land surface extends seaward from a central ridge, 800 to 1200 feet high, that runs from east to west almost the entire length of the island. The few flat areas are found for the most part in Charlotte Amalie, the seat of Government of the Virgin Islands, and a few alluvial-filled embayments. These embayments in general are less than a few acres in area with thicknesses of the alluvial deposits at a maximum being generally less than 50 ft (15.2 metres).

The climate of St. Thomas is tropical and the mean annual temperature is 78°F (25.6°C). In Winter the average low is 76°F (24.4°C) and in Summer the average high is 84° F (29.0°C). While north-easterly and south-easterly winds are relatively common, the prevailing winds are from the east.

The average annual rainfall on St. Thomas is 45 inches (1,140 mm) and as is the case in all of the Virgin Islands, the eastern end of the island receives less rain than the western end. The uneven distribution of precipitation throughout the year places nearly half of the annual rainfall between August and November. Rain showers are usually heavy and last no longer than a few minutes. While hurricanes and tropical storms pose a constant threat to St. Thomas, prior to the passage of tropical storm Klaus in its formative stages in November 1983, the last hurricane to cause major damage occurred in 1928.

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The present population of St. Thomas is estimated to be about 47,500 with an estimated total daily potable water demand of 3.6 million gallons (13,644 $m^3$) or approximately 76 gallons (0.29 $m^3$) per person per day.

## 2. Sources of Supply

### (a) Rainfall Harvesting

Roof catchments with cisterns supply about two-thirds of the island's population with fresh water. Cisterns providing 10 gallons of storage for each $ft^2$ (0.41 $m^3$ for each $m^2$) of roof area are required by law for single-storey dwellings. Approximately 0.65 million gallons (2,463.5 $m^3$) of water is harvested daily from this source (Torres-Sierra and Dacosta, 1984).

Hillside catchments for rain-water harvesting, first used in 1926, were the first source of water for public supply in St. Thomas. By 1949, 27 acres (10.9 ha) of paved catchment area and 9.425 million gallons (1,326.5 $m^3$) of storage provided water for the newly constructed public water distribution system. Until barging of water from Puerto Rico was begun in 1955, these hillside catchments served as the primary source of water for St. Thomas (Adams and Associates, 1978). Today the catchments are in disrepair and, with the exception of the structure on the campus of the College of the Virgin Islands, are no longer used.

### (b) Ground water

While total daily safe yield is estimated to be between 1.3 and 1.5 million gallons (4,927 and 5,685 $m^3$), only approximately 0.35 million gallons (1,326.5 $m^3$) of water is supplied from ground water each day in St. Thomas (Peebles, Pratt and Smith, 1979; Jordan and Cosner, 1973). The remaining amount is available for individual domestic use from wells with very low yields. In general, ground-water quality is poor due mainly to sea-water intrusion and contamination from domestic waste from individual septic disposal systems.

### (c) Desalination

Desalination of sea water is the principal source of fresh water in St. Thomas. Current daily desalination capacity is 3.1 million gallons (11,749 $m^3$) from three desalination units. At present, average daily production is 2.5 million gallons (9,475 $m^3$) using two of the units. Of the desalinated water that is pumped into the distribution system daily, only 40 per cent is accounted for (Priede-Sedgwick, Inc., 1979). Approximately 70,000 gallons (265.3 $m^3$) of desalinated water is trucked daily from standpipes to users outside of the potable water distribution system.

## 3. The salt-water distribution system

### (a) History

In the late 1920s the United States Navy installed a salt water distribution system in Charlotte Amalie. The main lines were made of cast iron. This system was expanded to its present configuration in 1950 when six-inch concrete lined ductile iron pipes were used (personal communication with Mr. Pedrito Francois). The present salt-water distribution system is used for fire-fighting and sanitary flushing.

(b) The pumping stations

There are two salt-water pumping stations in Charlotte Amalie. The one generally used is situated on the shoreline on the western end of the town at Long Bay. At this station water is withdrawn directly from the harbour through a screened intake that is approximately 25 feet (7.6 m) away from the shoreline in 5 feet (1.5 m) of water. An electrical generator remains on standby for use at this station during the once-frequent power outages. When the sea is too rough and there is an excessive amount of suspended matter in the water, the alternate pumping station is used.

The second sea-water pumping station is located in central Charlotte Amalie on a filled area close to the waterfront. A shallow well on the site serves as a ready source of sea water which is free from the organic and other natural debris as well as plastic bags and other garbage from the harbour, which clog the screen at the other site.

(c) The distribution lines

The salt water distribution system of St. Thomas extends a distance of approximately 22,000 ft (6,706 m) from the College of the Virgin Islands in Lindberg Bay at the western edge of the town to Estate Thomas in the east. It has been estimated that 60 per cent of Charlotte Amalie, principally a highly developed area with hotels, restaurants, shops, offices and residences, is tied into the salt-water distribution system for non-potable purposes.

Only about 35 per cent of the 1.0 million gallons (3,790 $m^3$) of sea water pumped daily to the distribution system is accounted for at the public sewage treatment plants. An estimated 350,000 gallons (1,326 $m^3$) of the salt water distributed each day is used for continuous flushing of storm drains to the ocean. The remaining 300,000 gallons (1,137 $m^3$) of sea water is lost to leakage in the system (Torres-Sierra and Dacosta, 1984).

Pressure in the six-inch lines is usually maintained at between 80 to 90 pounds per square inch (5,624 to 6,300 $g/cm^2$). Corrosion-weakened pipes preclude sustained maintenance of higher pressures unless fire hydrants are in use. At such times, a system pressure of 120 psi (8,436 $g/cm^2$) is maintained.

It was determined that in at least one place a concrete tank was designed into the distribution system particularly to store water for fire-fighting purposes. This tank, built at an elevation of about 220 feet (67.1 m) on Bunker Hill, was filled when the pressure in the system was high. The tank was connected to a number of fire hydrants in the area and could also be used for sanitary flushing when the pumping stations were not on line. This tank is no longer in service.

As a consequence of the fragile condition of the distribution lines and the subsequent and necessary gradual lowering of the normal pressure maintained in the distribution lines, fewer areas on the hills surrounding Charlotte Amalie are currently receiving salt water. Piped salt water is not available at elevations about 180 feet (54.9 m).

## 4. Conclusions

While the salt-water distribution system of St. Thomas provides a readily abundant source of water for fire-fighting and sanitary flushing, there are drawbacks associated with the system. A significant one of these is the damage that leakage from the lines has done to the thin lens of fresh ground water in Charlotte Amalie. Before the inception of the salt-water distribution system, several shallow dug wells in the city served as a small but heavily-used source of water for residents. The salinity of the water in these wells has since increased to a point where they have had to be abandoned.

Introduction of large quantities of salt water into the sanitary sewer lines makes waste-water treatment difficult. This is especially true when consideraton is being given to reuse of waste water. The use of the salt-water distribution system in Christiansted, St. Croix has been reduced in order to lower the salt content of the town's waste water for irrigation and ground-water recharge.

Salt water generally adversely affects metal pipes used in household plumbing. Lately, plastic is being used more in plumbing and corrosion in fixtures is no longer as severe a problem as it once was.

Several arguments have been raised on the viability of the dual water system in St. Thomas. It is acknowledged by everyone that the salt-water mains, even if replaced at high cost, would still leak into the shallow fresh-water lens of Charlotte Amalie. While those against the system argue that this should be avoided at all cost, system proponents are quick to point out that wells in the city, which might possibly be used if the system was eliminated, could only supply a miniscule fraction of the demand.

In response to the concern that salt water introduced into the sanitary sewers make treatment difficult, supporters of the system maintain that reuse of treated waste water probably never will be practised in Charlotte Amalie, because the public will not support direct reuse and opportunities for reuse through ground-water reclamation are very limited. Additionally, it is argued that sea water has ample opportunity to leak into the sewer pipes in Charlotte Amalie and it is not practical to try to eliminate it.

Present practice in St. Thomas confirms that the days of an unlimited supply of water being available for fire-fighting are limited. There are no plans to expand the salt-water distribution system and repairs to the system are being made for the most part only when breaks occur in the lines. Though desalination costs are high, fire-fighting water supplies normally contribute less than one per cent of annual water consumption (Coffin and Richardson, Inc., 1981) and it is more cost-effective to use this expensive water for fire fighting and sanitary purposes than to invest in an additional separate distribution system with very high maintenance costs.

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Part Three

# COUNTRY AND REGIONAL PAPERS

# I. EXPERIENCES WITH NON-CONVENTIONAL WATER RESOURCES

## A. Bermuda: Application of non-conventional water resources

by E.N. Thomas*

### 1. Introduction

(a) Geography

Bermuda is a small, isolated group of islands situated at latitude 32° 19' North and longitude 64° 46' West. The nearest point of land, Cape Hattereas, North Carolina, is 570 miles to the west-south-west.

The main land mass of Bermuda, made up of seven principal islands, has an area of approximately 21 $mi^2$. It is shaped much like a fishhook with the length being 19 miles, the maximum width 1.6 miles and the average width one mile. The elevation of the land is on average 100 feet above Ordnance Datum (O.D.) and the highest point is 287 feet above O.D.

(b) Climate

Bermuda enjoys a frost-free, semi-tropical climate. There is no pronounced wet or dry season although the summer months of April, May, June and July have a higher percentage of rain-free days.

(c) Resident and tourist population

The resident population of Bermuda is approximately 55,000, of which some 41,000 are Bermuda-born and 14,000 are of foreign origin.

In 1984 a total of 528,871 tourists visited Bermuda, of whom 78.9 per cent arrived by air and 21.1 per cent arrived by cruise ship. The average length of stay was five nights. Bermuda's tourist industry is very seasonal, with the greatest number of visitors arriving during the months of May through October.

(d) Accommodations

The resident population is housed in 22,100 houses and apartment dwelling units. For the tourist population, 230 hotels, guest houses and self-catering apartments have a total bed count of 9,600 beds. There are 2,720 commercial and public buildings, including schools, post offices, hospitals, churches, offices, shops, restaurants, and warehouses.

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(e) Industry and Economy

Bermuda's two major industries are tourism and off-shore tax-exempt company business. There is no heavy industry and only a limited amount of agriculture (674 acres) and fishing. These do not meet the local demand and most foodstuffs, clothing, furniture, household appliances and luxury items must be imported.

(f) Geology

The islands consist of aeolian limestones deposited on the eroded cap of an extinct volcanic seamount. The top of the volcanic rocks varies between 50 feet and 400 feet below sea level.

The limestones are interbedded with palaeosols, the sequence reflecting climatic and sea level changes in the Pleistocene era. The limestones consist of sand-sized, reworked debris of the coral reef environment and were deposited in a sequence of overlapping dunes by the prevailing winds.

There are three main units of limestones which are distinguished by their degree of diagenetic alteration by percolating rain water. These units are:

(i) Paget Formation

This is the youngest, least altered rock type and is a well-sorted, loosely-cemented, granular limestone with some aragonite (35 per cent by weight) and magnesium calcite (50 per cent by weight). The interconnected porosity is high (25-40 per cent), and permeability is intergranular. The topography consists of pronounced dune-shaped hills.

(ii) Belmont Formation

Older than the Paget Formation, the Belmont Formation has experienced a greater degree of alteration. The permeability is therefore considerably greater, due to the development of many pencil-sized solution channels. Some of the magnesium calcite and aragonite has been converted to more stable calcite. This is precipitated between the original grains, increasing the degree of cementation and reducing the intergranular porosity.

The topography of the Belmont Formation consists of gently rolling hills. Much of the topset beds of the original dunes have been eroded, giving a more rounded appearance to the land.

(iii) Walsingham Formation

This is the oldest, almost totally altered unit. It is a very hard limestone, consisting almost entirely of secondary calcite. It contains many well-developed caves and large solution channels. It is restricted geographically to a small area of the island which, as with the Belmont Formation, has a smooth, rounded topography resulting from the erosion of the tops of the dunes. The palaeosols and present-day soils are thin, on average 6 to 12 inches thick.

(g) Hydrogeology

The quality of the ground water is primarily dependent upon the rock type. There are five lens-shaped fresh-water bodies in "Ghyben-Herzberg" equilibrium with the underlying sea water. These occur only in the Paget Formation, which has the highest porosity and the lowest permeability.

In the Belmont Formation, which has a higher permeability than the Paget Formation, there is more mixing of the fresh recharge water with the underlying sea water, due to the easier transmission of tidal fluctuations through the aquifer. These rocks therefore contain brackish ground water.

In the Walsingham Formation, which has almost infinite permeability, the percolating rain water mixes completely with the sea water. Cave pools are of sea-water salinity below a thin, very brackish, surface layer.

## 2. Sources of water

(a) Roof and ground catches

There are no rivers and streams in Bermuda, and the waters of the small inland lakes and ponds, which stand at near sea level elevation, are very brackish. Until 1930, the only source of water for the population was rainfall catches.

Fortunately, rainfall is high, and spread evenly throughout the year with no long-term seasonal drought period. Even today it is estimated that 95 per cent of the population relies solely upon roof catchments for its water supply.

The roofs of the houses are traditionally adapted to catch rain water. The standard roof consists of overlapping Bermuda limestone slates on a wooden framework. The slates are painted white, using either a concrete and lime whitewash or a latex-based paint. Rain water is guided along the roof by "glides", which are wedge-shaped limestone lips, to downpipes, and discharges by gravity into storage tanks, commonly located underneath the building. Small electric pumps are used to transfer the water from the storage tanks through a pneumatic tank to the water fittings in the house.

Some hotels and homes have additional ground catchments to collect water. These are sloping hillsides which have been cleared of growth and soil, concreted and painted.

The construction and maintenance of roofs, ground catchments and water storage tanks are controlled by the Health Department. The Public Health (Water Storage) Regulations 1951 require that either 80 per cent of the roof area be guttered for catching rain water, or that a ground catchment of equivalent size be provided. Storage tanks must have a capacity of 10 Imperial gallons per square foot of catchment, which is the equivalent of four months' rainfall based on an annual average of 57.6 inches. Roofs are normally washed, cleaned and painted every four years, but tank emptying and cleaning for domestic premises is a rare requirement.

The additional cost of adapting a roof as a rain-water catch is negligible; the saving on the cost of gutters offsets the cost of the glides. However, the provision of the water storage tank and pump adds approximately 7 per cent to the cost of construction of a house or bungalow, and has to be considered as the cost of providing the premises with a supply of potable water.

(i) Yield of roof and ground catchment

It is estimated that 75 per cent of rain which falls on catchments is collected. There is some loss due to evaporation (when short light showers are interspersed with sunshine), and to run-off during periods of high intensity rainfall when the glides or gutters and downpipes cannot cope with all the water running off the roof.

(ii) Calculation of average annual yield of water catches

| Catches | Number | Average roof area | Total catch area |
|---|---|---|---|
| Roof catches | | | |
| Residential properties | 15,000 a/ | 1,500 $ft^2$ | 18 million $ft^2$ |
| Commercial properties | 1,500 b/ | 5,000 $ft^2$ | 6 million $ft^2$ |
| Total roof catch area | | | 24 million $ft^2$ |
| Average annual yield per $ft^2$ of roof | | | 29.9 gallons |
| Average annual yield of roof catches | | | 717.6 million gallons |
| Ground catches | | | |
| Average annual yield | | | 35 million gallons |
| All water catches | | | |
| Average annual yield | | | 752.6 million gallons |
| Equivalent daily yield | | | 2.1 million gallons |

a/ There are approximately 15,000 residential properties in Bermuda, providing a total of 22,100 dwelling units (houses and apartments).

b/ There are approximately 1,500 commercial buildings which house 2,710 commecial properties.

(b) Ground water

(i) Public supply

In 1931 a local private company, Watlington Waterworks, Ltd., was incorporated to abstract water from the main central lens to supply the públic with non-potable quality water for washing and toilet flushing. Over the years the company developed a limited distribution system with about 800 consumers and, at a later date, installed an electrodialysis plant to provide some major hotels with drinking water.

The Public Works Department (PWD), commenced ground-water research and development in 1969 to meet the growing public demand for water in dry weather spells and as an alternative to multi-stage flash (MSF) distillation of sea water for the supply to Bermuda's two hospitals.

In April 1979 the Public Works Department and the company entered into a joint venture, primarily to turn the supply of the latter from non-potable to potable and arrest the over-abstraction occurring in a section of the central lens.

Today the joint operators have a combined total of 110 wells abstracting brackish water, which is desalinated, and 99 wells and 12 galleries and tunnels abstracting potable quality water.

Combined licensed abstraction capacity is 1,150,000 gallons per day. Hospitals and seven major hotels account for 55 per cent of the sales to some 1,000 consumers connected to the limited distribution system.

Annual sales for the five years operation of the joint venture are set out below:

Water Sales (1,000 gallons)

| | 1980 | 1981 | 1982 | 1983 | 1984 |
|---|---|---|---|---|---|
| Annual total | 225,466 | 225,720 | 230,965 | 222,942 | 230,722 |

In addition to the development of the central lens, the Public Works Department has developed a lens towards the western end of the island and utilizes the potable nucleus to supply four water truckers servicing that area. Development of the small lens at the east end of the island has also commenced and, with desalination of the brackish water, is currently providing 60,000 gallons of potable water per day.

(ii) Commercial abstraction

Three water truckers are licensed by the island's Water Authority to abstract water, and licensed by the Health Department to supply the public with potable water. The water in all cases is brackish and treated by reverse osmosis. One licensee abstracts potable quality water and provides supplies to water truckers.

Some hotels, guest houses and commercial premises abstract ground water for flushing, air conditioning coolant, and to supply their own desalination plants. The quality of the water varies from brackish to near sea water levels of total disolved solids (TDS).

(iii) Water truckers

While water truckers are not a resource in terms of the island's water balance, it will be appreciated that with a limited main distribution system, which has only been delivering potable water since 1979, water truckers provide a most essential service.

With the increase in water consumption due to the greater use of dishwashing machines, sink waste disposal units, jacuzzis, and multi-storey apartment developments, the traditional roof catchment is not always sufficient to meet the water needs of the premises, especially during dry spells. Consequently many guest houses and domestic properties require a make-up supply of potable water. Those households where the public water supply is not available must purchase water by the 1,000 gallon load from a water trucker. Water trucks licenced by the Transport Control Department are owned and operated by private contractors, and by the PWD which has two to cater for Government's needs.

Water truckers may obtain their water supplies from Government, privately-owned resources, or from under-used storage tanks, particularly those provided for commercial properties where water consumption is low. Churches and warehouses frequently have water surpluses over their requirement in storage.

Government sales to water truckers vary from nil in winter to 850,000 gallons in a dry weather month. On overage, water truckers draw 2 million gallons per annum from Government's outlets.

(iv) Domestic abstraction

An alternative response to increased consumption, or insufficient roof catch/tank size, is to drill a well for domestic water supply. There are approximately 2,200 registered domestic boreholes throughout the island, licensed to abstract up to 150 gallons per day for flushing, washing and other non-potable uses. As this is nearly all returned to the aquifer via cess pits, this use is considered to be non-consumptive.

(c) Desalination

Overall island demand for potable water exceeds that which can be met from roof catches and potable ground-water production alone and the deficit is made up by the desalination of brackish ground water and sea water.

(i) Brackish water desalination

In the reverse osmosis (RO) process, the feed water is forced under pressure through a semi-permeable membrane which restricts the passage of dissolved semi-permeable membrane which restricts the passage of dissolved salts. A lower TDS product is created, while the dissolved salts build up on the feed side. Approximately 25 per cent of the feed water is rejected with the removed salts. Disposal of the reject water is via a deep, sealed borehole, to prevent saline contamination of the ground water, or by direct discharge to the sea.

The Bermuda Government has two brackish-water reverse osmosis plants. The larger of the two, commissioned in July 1981, has three units, each capable of producing 125,000 Imperial gallons per day (Igpd). Two units operate with low membrane pressure (250 pounds per square inch or psi) and the third unit uses a higher pressure membrane (300 psi). The brackish feed water, with an average TDS of 1400 to 1750 ppm is supplied from 55 wells. The product water has a TDS level of 210 to 350 ppm. This is blended with raw well water to bring the TDS to 490 ppm, within WHO quality standards. The blend is put into supply after chlorination.

The Government's second brackish-water RO plant (commissioned in July 1984) produces 60,000 gpd and is supplied by 15 wells. The membranes operate with low pressures of 250 psi. The TDS levels of the feed and product waters are similar to those of the larger plant. The total cost of production, including amortization of capital invested, is approximately US$ 6.50 per 1,000 gallons. There are four additional reverse osmosis plants in operation in Bermuda. Two supply Cottage Colonies and two are operated by water truckers.

The electrodialysis process uses cation- and anion-specific membranes. When direct current potential is applied across the brackish feed water, the cations (Na+, Ca++, Mg++) move towards the cathode (negative electrode) and the anions (Cl-, HC3-, SO4--) migrate to the anode (positive electrode). The cation- and anion-specific membranes, which permit only the passage of cations and anions respectively, prevent remixing and the movement of ions back into the fresh water. The membranes are stacked such that the fresh, pure water can be collected from one compartment and the concentrated salt solution can be rejected.

The Water Company operates a 250,000 Igpd electodialysis plant in Bermuda. The process is economical if the feed water has a TDS of less than 1400 ppm. If the TDS is higher, the costs rise dramatically. The volume of reject water is quite low, running at about 15 per cent when the feed water is below 1400 ppm TDS. The estimated cost of production id US$ 6.50 per 1,000 imperial gallons.

(ii) Sea Water Desalination

Reverse Osmosis. In principle this is the same process as for brackish feed water. However, operating pressures across the membranes are much higher and of the order of 800 psi. The plant therefore requires heavier-duty fittings, and incurs higher capital and operating costs. There are four sea water RO plants on the island, one operated by the airport catering company and three by hotels.

Distillation. Prior to the development of the reverse osmosis process for the desalination of sea water and the development of ground-water resources, multistage flash (MSF) distillation plants were installed in Bermuda by the major hotels and Government for the production of potable water.

Only three plants in three major hotels and one at the US Naval Air Station remain, and are maintained operable principally as standby facilities. The considered advantages of the distillation process were that the product was very pure (suitable for boiler feed water and delicate hospital equipment).

The disadvantages were many. By the mid-1970s the plants were very costly to run and maintain, and required full time supervision. Also there were constant problems with corrosion and scaling. By the mid-1970s the product water cost on average US$ 18 per 1,000 Imperial gallons, which compared unfavourably with the developing reverse osmosis process.

Calfran Process One. This is an entirely new process of desalination which is being developed in Bermuda by a private company and is on the verge of being produced for the commercial market. It is a hybrid freeze-evaporation process which operates as follows.

Feed watér is injected into a cooling chamber which is under reduced pressure. The feed solution is taken below the critical point (triple point) so it spontaneously converts from a liquid to a mixture of ultra-pure water vapour, process ice and waste brine containing the contaminants. The pure water vapour (product water) is condendsed using the mixture of ice and waste brine as a coolant).

The Calfran Process One is stated to have many advantages over the existing desalination processes. It is expected that the capital and maintenance costs of the Calfran Process One will be substantially less than those of the existing systems because of its simplicity.

It operates at very low temperatures and as a result there is very little corrosion of the component parts. The condenser is mainly made of plastic, with little metal, which eliminates galvanic action. Also it operates under low pressures, obviating the need for expensive pumps. There are no delicate membranes to become fouled, scaled or to need careful storage and cleaning. There is no requirement for pre-treatment of the feed water or regulation of the pH, which reduces the cost of chemicals.

There is very little volume of feed water rejected; indeed, if the system were left to run with no additional feed water input, the reject would be in the form of dry salt crystals. The product is extremely pure and can, for example, be used directly in haemodialysis units.

Full details of the operation, maintenance, and costs are expected to be released at the International Deslination Association (IDA) conference held in Bermuda in November 1985.

(iii) Salt water dual dystem

The Bermuda Government encourages the use of non-potable saline water for flushing to reduce the demand for fresh water in parallel with piped potable systems. Substantial savings are possible.

Many hotels, offices, the Civil Air Terminal, prison and Government housing complexes use saline well water for flushing and as an air-conditioning coolant. It is estimated that in the Government's Prospect housing complex alone (about 210 dwelling units), 8,000 gpd of salt water is used, saving an equivalent quantity of potable water. Over the island as a whole, a rough estimate of 500,000 gpd is used in this way during the summer months.

Where buildings with salt water flushing systems overlie a fresh or brackish lens, deep sealed boreholes are required for the disposal of (treated) effluent to avoid contamination of the ground water.

3. Sewage effluent recycling

(a) Cess pits

The traditional method of sewage disposal in Bermuda is to use unlined cesspits. The size and construction of these is governed by Public Health regulations.

Concern has been expressed at the potential for sewage pollution of ground-water resources. Studies carried out to date however, indicate no bacteriological pollution, but significantly higher nitrate levels. It therefore appears that the natural limestone acts successfully as a filter for suspended solids, permitting reuse of waste water as a component of the ground water resource.

(b) Sewage treatment plant

One major hotel has an extended aeration, activated sludge plant, the product of which is used to irrigate its 18-hole golf course. The hotel has a dual water system, using rain water and brackish well water for toilet flushing. The flow through the sewage plant varies between 150,000 and 250,000 gallons per day, depending upon the occupancy of the hotel. Due to the rapid fluctuations of hotel occupancy, the plant effluent is of variable quality, partly buffered by storage in a three million gallon polishing pond.

Chlorides in the sewage effluent fluctuate between 2,500 and 3,000 ppm. This is diluted in the polishing pond by water draining from the roads, parking lots and golf course. The chlorides in the water used for irrigation are usually between 1,200 and 1,500 ppm.

At present irrigation of the golf course consumes about 200,000 gallons of water per day. The greens are irrigated on a rotational basis, 6 nights per week for the four summer months and about 3 nights per week for the balance of the year. Estimated annual irrigation consumption is about 40 million gallons.

It is also planned to use the treated sewage effluent in place of sea water as make-up cooling water for the hotel. The high elevation of the hotel means that pumping sea water is expensive where little expense would be incurred in diverting the effluent through the cooling towers. Some modification of the sewage plant will be necessary, as a consistently high quality effluent will be required. An estimated 25,000 to 30,000 gallons per day will be used as make-up water.

(c) Grey water for irrigation

Grey water is waste water from kitchens and bathrooms excluding flushing water. It contains soap and grease but no sewage.

At a recently-completed complex of time-sharing apartments, grey water will be returned to Government and the treated product water used to irrigate the greens and tees of a new 18-hole public golf course, due to be opened in 1985.

The water from showers, baths and wash basins (about 10,000 gallons per day) will be delivered to a holding tank. From there it will be processed through a grease trap, septic tank and an upward clarifier. Finally it will be chlorinated and pumped to storage, ready for use as irrigation water. The storage tank has been carefully sited so that, when water is not required for the golf course, the tank overflow will percolate to the water table and contribute to the recharge of the lens.

(d) Recycling laundry water

In one major hotel laundry waste water is recycled. The water from the wash and rinse cycles is processed through a skimmer and pressure filter and then reused in the laundry as wash water.

The recycling unit saves the hotel an average 6,000 gallons of potable water per day. An additional saving arises in energy required to heat the water. At a cost of $US 9.00 per 1,000 gallons, this represents a savings of approximately $US 20,000 a year plus energy savings.

(e) Hydroponics

This is the cultivation of plants in water without a soil medium. One local agriculturist uses this technique to grow tomatoes. Nutrient-rich water is constantly aerated and circulated and the pH is monitored daily. The system is self-contained with approximately 800,000 gallons per year of rain water being caught by the 35,000 $ft^2$ of greenhouse roof and stored in a 250,000 gallon tank. The tomatoes require up to 3,000 gallons of water per day to produce 4,000 lb of fruit per week. The water is circulated around the plant roots. To reduce the risk of bacterial build-up, the water is drained off and replaced on a weekly batch basis.

## 4. Energy recovery from solid waste for water production

The population of Bermuda produces some 40,000 tons of refuse each year. At the present time the island's refuse is being shredded and used as landfill but due to a lack of further landfill capacity and a shortage of suitable cover material, the Government has decided to build a refuse incineration plant with energy recovery facilities.

In the planning of this facility, consideration was given to the use of the waste heat of the incineration process (in the form of steam) to produce potable water. Studies were made of the following:

(i) Distillation of sea-water using steam;

(ii) Production of electricity for use in reverse osmosis for treatment of either brackish or sea water;

(iii) As (ii), above, but the exhaust steam from the turbo-alternator being used for the distillation of sea water.

Incineration of refuse as a method of refuse disposal requires a 24-hour, 7-days-per-week continuous operation throughout the year. Particularly during the months of November, December, January and March the Public Works Department and Watlington Waterworks jointly have surplus resources and potable water production capacity. Consequently, for Bermuda the best financial option, in utilizing the heat energy from solid waste available, is to maximize the production of power for sale to the local electric light company. If in future years it becomes necessary to turn to the desalination of sea water, the power generated remains available for this purpose.

Acknowledgments

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## B. Cayman Islands: Country situation report

by R.G.B. Beswick*

### 1. Introduction

(a) Location

The Cayman Islands, three relatively small limestone islands, are located south of Cuba in the western part of the Caribbean (see map 2). Grand Cayman, largest of the three islands, is western most and the seat of Government. Cayman Brac and Little Cayman are approximately 60 miles north-east of Grand Cayman.

(b) Hydrology and hydrogeology

The average annual rainfall collected at the airport, which is situated at the western end of the island, between the period 1920-1984 was 60.4 inches, with a maximum of 83.50 inches and a minimum of 37.72 inches. Of the years recorded, 63 per cent were below average.

The distribution of rainfall throughout the island is irregular with the eastern region being significantly drier. The eastern region has an annual average of 44.40 inches with a maximum of 69.65 inches and a minimum of 18.90 inches. Of the years recorded, 50 per cent were below average.

The island is tropical with a wet and dry season. The rainy season is generally from May to October, most rainfall occurring during September and October. February, March and April are the driest months, often with an insignificant amount of rainfall.

The average temperature during the season is $84^{\circ}$ F with high humidity. A $10^{\circ}$ drop is experienced during the dry season with a corresponding drop in humidity.

The sea experiences tides of relatively low amplitudes. Maximum tidal range is in the the order of 24 inches, while average tidal movement is approximately 14 inches.

Grand Cayman consists of a central core of flat lying limestone of Oligocene-Miocene age which is unconformably overlain by Pleistocene reef limestone. The Tertiary limestone is crystalline and ground-water movement is via fissures and solution channels. The Pleistocene rocks are less consolidated and water movement is generally intergranular.

Originally five fresh water lenses of significant size were identified to be of sufficient size to develop for a public water supply. More recently two of these lens, George Town and West Bay, have suffered through

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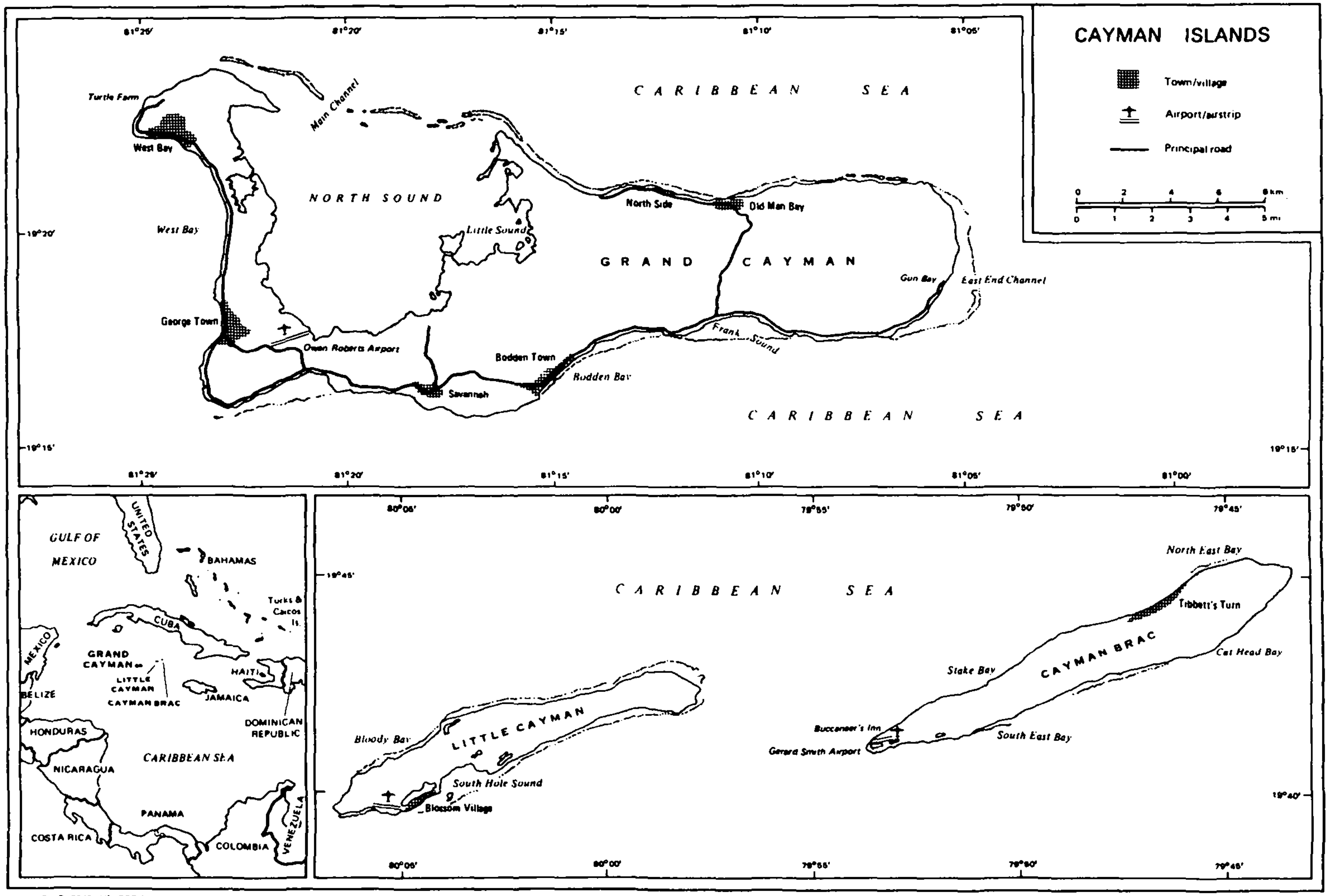


MAP NO. 2949 UNITED NATIONS
JULY 1977

Map 2. Cayman Islands

over-abstraction and pollution and are now no longer considered viable. A third lens, Lower Valley, has been subject to large-scale indiscriminate abstraction from commercial wells. This is now controlled, and the Water Authority has developed this lens with a well field and provides treated water at a reservoir. The two major lenses are located at East End and North Side, both areas remote from the developed part of the island. The Water Authority has developed part of the East End lens with a well field and provides treated water at a reservoir.

The latest available data suggest that the three major lenses can provide up to a total of 1,000,000 gallons per day. This data is being updated as now better access to the major lenses is possible. It is expected that this will show that more water is available than was previously anticipated.

(c) Population

The population of the Cayman Islands is made up of the full time residential sector and the tourist sector, the latter comprised of residential tourists and cruise ship visitors.

The full time residential population was last enumerated in the census of 1979 and amounts to over 16,600. Tourist populations vary but in 1982 the number was 130,763 in addition to the 177,215 cruise ship visitors.

Based on the 1979 population, it is predicted that the resident population will grow to over 31,000 by 2000, applying a 3 per cent growth rate for residents.

(d) Economy

The economy is based almost entirely on tourism and the off-shore financial industry. At ths time there is no manufacturinmg industry other than a cement block factory, a ready mix plant, quarries and a small fabrication plant. The remainder of the businesses support the tourism and financial sectors.

Agriculture is mainly of a subsistence nature, except that several operations are developing to produce horticultural produce on a commercial basis. The Government is promoting agriculture in an attempt to develop an industry capable of producing a consistent product and thereby reducing the almost 100 per cent reliance on imported food stuffs.

The 1982 foreign trade figures showed visable trade imports at CI$ 110,000,000[1/] and exports at CI$ 2,000,000.

The United Nations estimates the annual per capita income at US$ 3,000.

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1/ $US1.00 = $CI 0.83.

## 2. Water supply and sewage disposal

### (a) The Water Authority

The Water Authority was established as a Statutory Body in 1983. The Water Authority Law 1982 vests ground water in the Crown and requires that the Authority protect and manage the resource. The Law also requires that the Authority provide public water supplies and public sewerage systems. The Water Authority Regulations were promulgated in March 1985 and the Authority now has the framework in which to operate.

The affairs of the Authority are managed by a Board appointed by Government and the Chief Executive Officer; the Director administers the Department. Prior to the establishment of the Water Authority there was no control over water resources nor any ability to address the escalating water and sewage problems.

### (b) Typical water supply and sewage disposal

Traditionally, households have satisfied their own water requirements on site, either by individual rain-water catchments with concrete cisterns, ground water abstraction or a combination of both, the latter being the most common. Treatment and disposal of waste water is also accommodated on-site; using either a septic tank or cesspit, effluent is discharged into the ground water by soak away or deep injection well.

In the majority of cases households have a fully piped plumbing system, pressurized by small electric centrifugal pumps. Households with both well and rain-water catchment would generally provide separate pumps, but not necessarily separate plumbing systems. Most households utilize water-borne sanitation.

Table 54 shows the types of water and sewerage facilities utilized by households in the George Town area. These data were obtained in the domestic water and sewerage survey carried out by the Water Authority in 1983. The survey reached approximately 80 per cent of all households.

In the more developed areas, the large number of properties utilizing on-site sewage disposal is a great risk to ground water quality. This is particularly true in those areas where the high water table precludes gound filtration of effluent. Regular domestic well-water monitoring programmes are carried out, and these do show high levels of faecal contamination. It is not common for individual households to treat ground water before using. In the George Town area, which is 3.47 $mi^2$, there exist 1484 sources of ground water pollution (household sewerage facilities) and a population of 5189 using ground water. Organic contamination of ground water in many of the developed areas renders it too odourous to be used by individuals.

Rain water storage systems are also not free from the risk of contamination, and testing programmes have shown significant levels of faecal contamination.

Table 54. Cayman Islands: Water and sewerage facilities in the George Town area

| | Water facilities Houses (No) | Persons (No) | Persons (%) | | Sewerage facilities Houses (No) | Persons (No) | Persons (%) |
|---|---|---|---|---|---|---|---|
| Ground water only | 225 | 886 | 15 | Septic tank | 848 | 3,265 | 57 |
| Rain water only | 120 | 462 | 8 | Cesspit | 523 | 2,013 | 35 |
| Combination | 1,123 | 4,232 | 76 | Pit latrine | 113 | 435 | 8 |
| | | | | No facilities | 3 | 11 | -- |
| No source | 19 | 73 | 1 | | | | |
| Total | 1,487 | 5,724 | 100 | | | | |

There is no doubt that the per capita demand for water has increased as a direct result of modern facilities, resulting in rain-water catchment systems being unable to meet demand. This is an increasing problem in many of the large apartment complexes where the catchment area is small in relation to the persons accommodated.

(i) Efficiency of individual systems

The efficiency of a rain-water catchment system is a function of rainfall, roof area, catchment equipment and demand. The domestic water and sewerage survey showed that an average household accommodates 3.85 persons, the house has a roof area of 1100 $ft^2$, and, where a cistern is provided, it is of volume 7,750 gallons. It also showed that average cistern water consumption per capita per day is 23 gallons where a dual supply is available and 38 gallons per capita per day where the household relies totally on cistern water.

Figure 37 indicates the average monthly rainfall collection and its consumption for the two per capita demands. It can be observed that such a system is 6,430 gallons in deficit per annum where the per capita demand is 23 gallons per day and 27,600 gallons in deficit where the per capita demand is 38 gallons per day.

The average annual collection is 25,794 gallons, which could provide an average household with 18 gallons per capita per day. This assumes 7,500 gallons of storage is available in order to store excess water during the wet season.

average situation 3·85 person household

1100 sq ft roof area

av. annual rainfall 64·42 in

rain collected 25,794 gall

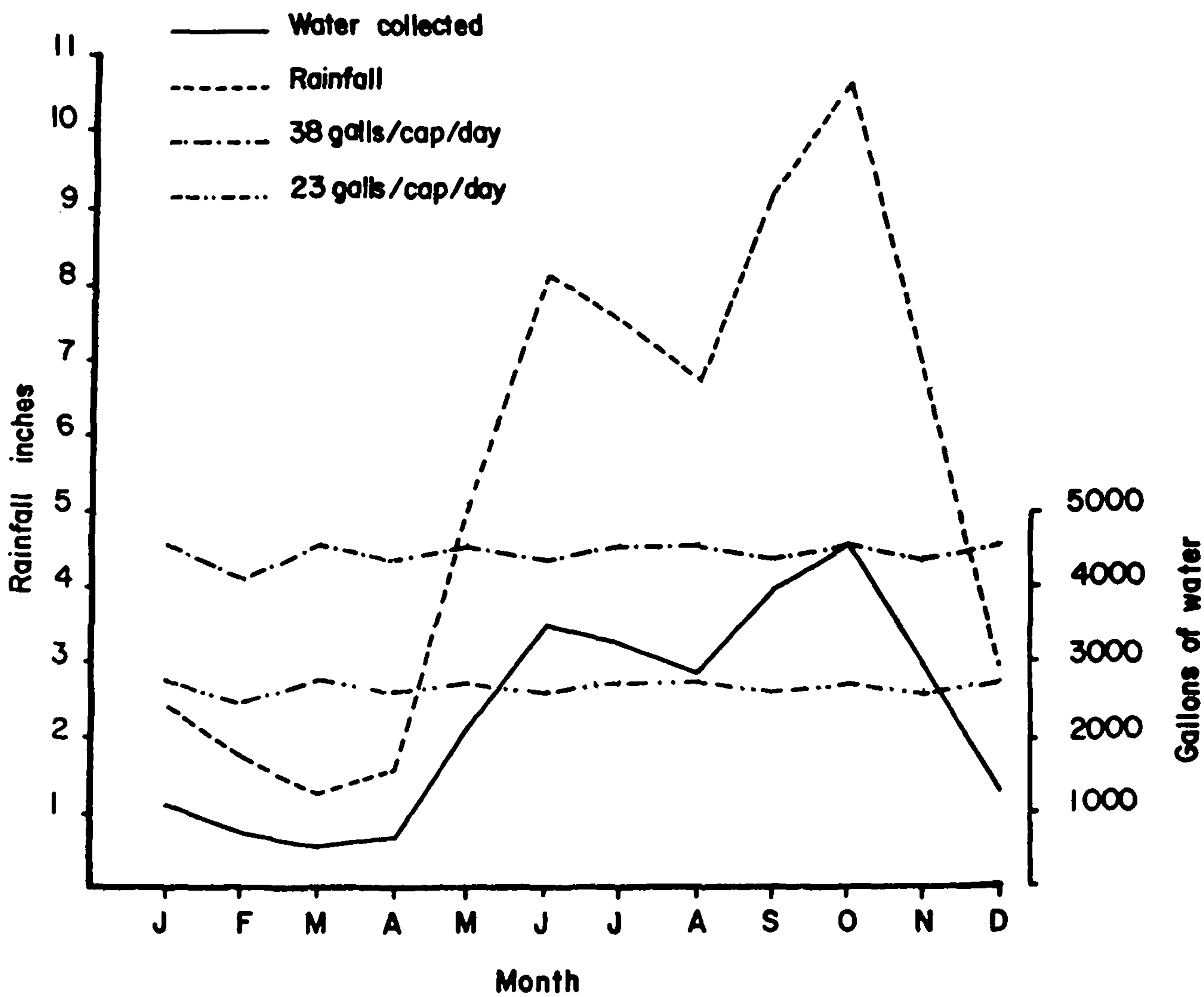


Figure 37. Rain-water collection in the Cayman Islands

The ground-water resources exist as relatively shallow fresh water floating on sea water; the development of these resources is difficult as the permeability of the rock is low. This results in the possibility of salt water intrusion occurring if water is abstracted at rates much higher than 2 to 5 gallons per minute. For this reason individual household wells often overuse the ground-water system and result in individual wells being inadequate to supply sufficient fresh water.

(ii) Cost of Individual systems

Rain-water Catchment

| | |
|---|---|
| Average size cistern is 7750 gallons | |
| Cost of construction at CI$ 1.00/gallon | CI$ 7,750 |
| Cost of pumping equipment, plumbing, etc. | 1,150 |
| Total | 8,900 |
| Capital amortized over 20 years at 14.5% (Mortgage period of house and bank rate) | |
| Annual amortization cost | 1,208 |
| Annual operation and maintenance | 700 |
| Total annual cost | CI$ 1,908 |
| Cost/1,000 gallons | CI$ 73.98 |

The construction costs in Cayman Island are obviously high and therefore it is important to realize that there is an optimum size for a storage tank, dependent on the collection area and location of the property.

Well Water

The cost of a bored well is currently CI$ 15 per foot for a 5-inch bore. Depths vary from 12 to 30 feet. Dug wells are generally more costly, but not practical for depths greater than 12 feet. Pumping equipment costs are approximately the same as that for rain-water catchments.

| | |
|---|---|
| Total capital cost of system | CI$ 1,400 |
| Annual cost (including amortization and operation) | CI$ 900 |

(iii) Desalinated water supplies

A private water company, the Cayman Water Company, provides water via a pipeline to properties within a franchise area designated by Government. This area is the Seven Mile Beach, where the majority of the tourist accommodations are located.

The company operates in accordance with the Water Supply and Production Law (1979). The franchise is now administered by the Water Authority, and a 7.5 per cent royalty on all sales is payable to the Government.

The company produces up to 685,000 US gallons per day by means of a vapour compression process, using diesel engines as prime movers. The company operates Meco equipment, four 50,000 gallon per day units, two 150,000 gallon per day units and one 185,000 gallon per day unit. The latter unit has only recently been acquired, the four smaller units are now eight years old and will shortly be replaced. The company has 1,800,000 gallons of storage capacity, which is barely sufficient to accommodate demands during the dry season, particularly as 10 per cent of production is sold to trucking companies.

Water is sold at CI$ 15.87 per 1,000 US gallons plus a fuel adjustment factor which fluctuates between CI$ 1.50 and CI$ 2.50 per 1,000 US gallons.

Many of the older establishments in the franchise area have some form of storage and still collect rain water; however, the majority of the more recent developments which are generally of a larger size rely totally on the Water Company supply. A number of the older establishments have also reduced their use of potable water by utilizing sea water for flushing toilets. A number of tourist accommodations outside the franchiese area have invested in sea-water reverse osmosis equipment. The largest is an 80,000 gallon per day plant and the smallest is a 10,000 gallon per day unit. There are a total of five RO units on the island. Without exception, all of these units have caused their owners considerable problems. The major problems are: quality of feed water, which affects the membranes; inability of high-pressure pumps to operate satisfactority; manufacturers' unreliability and inability to apprise owners fully of their maintenance commitment and the level of expertise required.

(iv) Water Trucking

Seven companies operate as water truckers, using trucks varying in size from 2,000 gallons to 7,000 gallons. These companies obtain their water from three sources: Water Authority well fields and reservoirs; The Cayman Water Company; and two private wells.

The Water Authority provides on average 2.62 million gallons per month and the Water Company 1.12 million gallons per month. The water truckers utilize about 0.26 million gallons per month abstracted from two private wells. The trucking companies sell water at costs between CI$ 20-50 per 1,000 US gallons, depending on type of water and destination.

The Water Authority sells water at its reservoirs for CI$ 4.58 per 1,000 US gallons. The Water Company sells water at its reservoir for CI$ 3.80 per 1,000 US gallons plus the fuel adjustment factor. The Water Authority has no control over the truckers' operations except the abstraction from the two private wells.

## 3. Proposals for water supply

The Water Authority is actively developing plans to provide the major developed area of the island with a public piped water supply. Currently, its major concern is the George Town area, where supplies are inadequate and where ground water is contaminated.

A joint venture with the Electricity Generating Company to utilize waste heat for distillation of water is under way, and a feasibility report is being prepared. The Company has available four 4.24 MW diesel generators and is proposing that an additional 16 MW be made available in 1987. It would appear that the waste heat generated from these installations would satisfy the demand for make-up water in the George Town area. It is also apparent that such water can be produced at a lower cost than piping ground water from the eastern part of the island. The IDE Multi-Effect plant would appear to be well worth considering both from an economic and operational point of view.

One other advantage of having a water supply in this area is that it would provide a second option for the West Bay Road Franchise area should there be problems wih the Cayman Water Company equipment.

The Water Authority has so far constructed two well fields, treatment works and reservoirs. One 60,000 gallon per day development with a reservoir capacity of 200,000 gallons is located on the Lower Valley lens and a second on part of the East End lens. This is a 90,000 gallon per day well field with a reservoir capacity of 100,000 gallons. Both these developments supply water to the truckers, each trucker hires a metered stand pipe and the system is fully automatic with no operator required.

Recent water shortages caused by the Water Company breakdowns, being unable to supply truckers and a large increase in demand, resulted in a rationing system at the Lower Valley reservoir.

The Water Authority proposes that in addition to its George Town development it will utilize its ground-water developments to pipe water to the settlements within their environs. Feasibility studies indicate that such supplies will be financially feasible and sufficient to provide a quality supply at much reduced costs to the consumer.

(a) Water demand

The 1983 demand for water is shown in table 55. The calculations from which this table was derived simplify matters by assuming that a resident requires 50 gallons per day and a tourist 100 gallons per day. They also assume that existing households relying totally on rain water will require, in addition to their existing supply, a further 25 gallons per capita per day and that all private ground-water abstraction will cease due to the unsanitary and unsafe nature of the abstractions.

Estimates of future demands are also shown in table 55. The predicted demands assume as increase of 3 per cent per annum in the residential population and 5 per cent per annum in the tourist population.

(b) Reuse of effluent

The Water Authority is proceeding with the provision of a sanitary sewerage system and sewage treatment works for the West Bay Road. Funding for this project has been obtained with constructdion to commence early in 1986 and completion late in 1987.

Table 55. Estimated daily water requirements in Grand Cayman, 1983-2000 (gallons)

| Sector | 1983 | 1990 | 2000 |
| --- | --- | --- | --- |
| Residential | 461,875 | 674,925 | 1,011,725 |
| Tourist | 24,900 | 45,100 | 89,300 |
| Municipal | 23,510 | 30,900 | 45,920 |
| TOTAL | 510,285 | 750,925 | 1,146,945 |
| Including 10 per cent losses and miscellaneous | 561,313 | 826,017 | 1,261,640 |

It is proposed that the treated effluent from the sewage treatment works will be used to irrigate properties along the West Bay Beach area. The most notable is a nine-hole golf course recently completed and now having to use desalinated water both from the Water Company and its own RO plant. There was concern that the salinity of the effluent might be too high for irrigation, as a number of the properties in the area use sea water for toilet flusing. The ground is poorly drained and as a reclaimed swamp is fairly high in salt content, obviously there is the potential for high salt accumulation in the soil. The Authority carried out a sewage survey and determined that the effluent will be of an acceptable salinity. The faecal caliform. BOD and suspended solids will also be acceptable as waste stabilization treatment is being utilized.

## 4. Conclusions

The Cayman Islands have developed to the point where they now are a successful tourist and business centre, utilizing completely non-conventional water resources. The time has now arrived, and the Government realizes this fact, that the resources that are available, be they non-conventional or conventional, should be used in a more efficient and economic manner. This will ensure that residents and tourists alike will benefit from a safe and less costly commodity which, when all is said and done, is a basic human right.

The Cayman Islands have developed in such a manner that individual rain-water catchment systems and wells are generally no longer adequate in terms of quantity and quality nor in many cases are they acceptable to the people.

It can be shown that public water supplies can be provided in such a way as to be financially acceptable and at the same time can satisfy the foreseeable demands.

The Water Authority has commenced its development of public water supplies and will continue on a phased basis, utilizing the islands' ground water resources and the waste heat available at the electricity generating plant for desalination

## C. China: The development and use of non-conventional water resources

by Song Xu-Tong*

### 1. Introduction

China, covering an area of 9.6 million $km^2$, is located in the east of Asia and faces the Pacific Ocean. The amount of total water resources is approximately 2,700 billion $m^3$, which ranks fifth in the world. The level of per capita water resources availability in China is a quarter of the global average. As a result of geographical position, precipitation is higher in the south-east of China than that in the northwest. Almost 45 per cent of the land is in arid and semi-arid areas where annual precipitation is less than 400 mm. There is a shortage of water supply for local residents in those areas, especially in some remote rural areas. Since the 1950s, as a result of industrial development and population growth, a number of cities, such as Dalian, Qingdao, Tianjin, Shenyang and Beijing, have encountered the problem of water scarcity in succession.

The country actively expanded its efforts to exploit conventional ground water and surface water resources, which now amount to 485.9 billion $m^3$. At the same time a lot of work has been done to develop non-conventional water resources. China has made some progress in sea-water and brackish-water desalination, waste-water treatment and reuse and rain-water collection and storage. The results show that non-conventional water sources need to be developed actively and that there is great potential and broad prospects in China.

### 2. Desalination

China has a long coastline of nearby 18,000 km with rich sea-water resources. Moreover, there are large areas having brackish water in five north-western provinces, the eastern part of north China and some coastal regions.

Desalination technologies have been developed in the country since the 1950s. Extensive research has been carried on the electrodialysis, reverse osmosis, distillation and solar processes and consequently, a large number of desalination stations have been established.

The sea-water electrodialysis desalination plant with a capacity of 200 $m^3$ per day in Sisha Yongxingdao Island went into operation in June 1981. There are 10 units fitted with domestic heterogeneous ion exchange membranes in the plant. The electric consumption is 18.1 $kWh/m^3$ for the total power and 15.2 $kWh/m^3$ for electrodialysis. The cost of water produced by electrodialysis is a quarter of that of water transported by ship. A wind-powered sea-water electrodialysis desalination plant with a capacity of 24 $m^3$/day was established in Chengsidao Island, Zhejiang Province, where

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abundant wind power is found. The cost of water produced has been greatly reduced, amounting to only one-fifth of that when utilizing the municipal electricity network.

In 1969 the first brackish-water electrodialysis desalination plant in China was established at a coal mine in Shanxi Province with a capacity of 100 $m^3$/day. The total dissolved salts of the brackish water can be decreased by that electrodialysis plant from 2,000 ppm to 500 ppm. Since the 1970s, a number of electrodialysis desalination plants have been built in Tanggu district, Tianjin City, where the ground water is brackish, containing high flourine. In addition, other plants for brackish-water desalination have been set up in Xinjiang, Gansu, Guangdong and other provinces.

The ruthenium-coated titanium wire electrode has been developed successfully for the electrodialysis anode and cathode. The electrodialysis reversal process has been adopted and new equipment reverses the polarity of the electrodes automatically and frequently by hydraulic drive. This effectively prevents scale from forming in the electrodialyzer, so that it can be operated stably for a long period of time without addition of any acid during operation.

In the reverse osmosis field, the cellulose acetate membranes, the aromatic polyamide membranes and a number of other synthetic membranes have been developed in China since the late 1960s. Reverse osmosis facilities consisting of tube, plate, spiral-wound or hollow-fibre modules have been manufactured and used in different industrial departments. In most cases, they are used for producing demineralized water and regenerating waste water, but application for potable water from brackish and sea water have not reached the practical stage as yet.

Research on brackish and sea-water desalination by large size distillation plant began in the 1970s in China. Recently, development of a distillation plant with a capacity of 100 $m^3$ per day has been completed and development of a larger plant has begun. Solar distillation plants applying the greenhouse principles for desalination of brackish and sea water were developed in China. Some solar distillation plants have sufficiently solved the problem of drinking water for local residents particularly in coastal islands and arid areas.

### 3. Waste-water reuse

In 1983 total municipal waste water discharged in China amounted to about 57 x $10^6 m^3$/per day, of which 76.7 per cent was industrial effluent and 23.7 per cent was municipal waste water. Only 17 per cent of the total waste water in the whole country is treated, however. Waste-water treatment facilities which have been built cannot meet the requirements of clean water and environmental considerations. As water resources become more scarce and water pollution becomes aggravated, more attention has been paid to the reuse of waste water.

In China, reuse of municipal waste water for irrigation has a long history. Part of the waste water is used for irrigation after being treated by primary treatment, either biological treatment or oxidation pond, and part of it is used directly for irrigation without treatment. Up until now the area irrigated by waste water has amounted to more than 10 million mu (13.33 x $10^3 km^2$ and 45 per cent of it is polluted to various degrees. At present, the country is setting about improving the quality of waste water for irrigation and strengthening its management. At present the effluent from Beijing Gaobeidian Municipal Waste Water Treatment Plant is used for irrigation after sedimentation only. However, a biological treatment facility is being planned to be constructed for improving irrigation water quality and part of the treated water will be used for industrial water recycling systems. In Shijazhong City, Hebei Province, experiments comparing irrigation by various waste waters which have been treated by primary or secondary treatment or oxidation ponds, are already in progress. Three waste-water treatment plants will be built in that city. In Dalian City, Liaoning Province, and Tianjin City, experiments on reuse of the waste water treated by advanced treatment were carried out while the facilities for projects of water transport from long distances were under construction. The cost of advanced treatment is Yuan 0.18 - $0.20/m^3$ (US$ 0.060 - $0.067/m^3$), which is 50 per cent lower than the cost of Yuan 0.38 - $0.40/m^3$ (US$ 0.12 - $0.13/m^3$) for water transported from a long distance. In other cities, for example, Qingdao, Handan and Taiyuan, municipal waste-water reuse systems are being planned on different scales for various industries. Aquacultural waste-water treatment projects have been built in succession since 1960 throughout the country. In Yarhu Lake, Hubei Province, Anda Town, Heilongjian Province, Boxing Country, Shandong Province, and other areas the waste-water treatment facilities which are used for fish culture, raising ducks, growing reeds, water hyacinth and lotus root, have been operated for many years. In recent years, research has also been started on an ecosystem engineering project which combines resources recycling utilization with natural purification and artificial treatment of waste water.

The focal point for conserving water and developing water resources is to increase the industrial water reuse rate. Although 60 per cent of municipal water supply is used for industries, the industrial water reuse rate is still low in China. According to the statistics from 110 cities, the average reuse rate for industrial water is only 24 per cent. Recently water saving activities have been expanding in many cities of the country. A lot of measures have been taken to popularize recycling of cooling water, adverse stream washing technology and other water reuse technologies. Therefore, the industrial water reuse rate is increasing continuously. In Dalian, Qingdac, Shanghai and Tianjin cities the rate of industrial water reuse is up to 75 per cent, 74.8 per cent, 64.3 per cent and 58.7 per cent, respectively.

### 4. Water supply and rain-water harvesting in rural areas

In recent years the rural economy has developed rapidly and the living standard in the countryside has risen continuously in China. In rural areas about 350 million people, or 40 per cent of the rural population, have access to clean drinking water and sanitation, but there are still 500 million peasants whose drinking water needs to be improved. Of those, 42 million people are short of water and another 45 million people are drinking water containing high fluorine, which exceeds the standard of drinking water. It is clear that there is a lot of work to do to realize the goals of the International Drinking Water Supply and Sanitation Decade. For this purpose, the Chinese Government drew up a programme in 1981, which set aside two years for preparation, three years for demonstration and five years for popularization. During recent years, the Government has been collecting money through many measures to increase the allocation of investment for water supply projects and has adopted various technical measures to solve the water supply problem.

It was estimated that the drinking water problem for 100 million people would be solved by the end of 1985, and afterwards the construction of water supply projects would further speed up year by year.

In some rural regions located in arid, rainless areas and on loess plateaus in the north-west and north of China, the traditional method has been to dig cellars for cisterns for storing water. Some progress with this technology has been made in Gansu, Shanxi and Ningxia Provinces during recent years. The water "cellar" has been an effective means to solve the drinking water problem for dispersed local populations. The rain water collected flows into a pool or pond for sedimentation and is then deverted to the cellar; a tablet of bleaching powder is added for disinfection, and the rain water is stored in the cellar. The water cellar looks like a jar in shape with its mouth and bottom being small and the middle being wide; the wall around it is lined with puddled clay mixed with hemp fibre and held together by "driving nails". The clay layer for the wall is 10 cm thick. The water stored in the cellar is drawn by handpump or water bucket and does not become mildewed after being stored for a long time. The amount of water stored in one cellar is enough for a household for one or two years.

In addition, some roof catchment facilities have been built in Henan Province. Passing through a pipe, the water collected on the roof flows into the underground or semi-underground water cellar for use. This kind of facility is characterized by no seepage through the roof, easy forming of rainfall run-off, less pollution, better water quality, easy construction and operation and cost saving. It is estimated that in the regions where the annual precipitation is about 400 mm, an area of 15 $m^3$ per capita catchment area for collecting rain water can ensure the people their basic needs.

## 5. Concluding remarks

China is a developing country. In the early 1980s the country set a goal to quadruple the gross output value of industry and agriculture by the end of this century. Therefore, it was forecast that water consumption would be greatly increased. Along with the development of conventional water resources, the non-conventional water resources should be developed rapidly. In practice, the following conclusions can be reached:

(a) The industrial and densely populated cities located in arid and semi-arid areas are the most active regions for development of waste-water reuse. With the amount of developed conventional water resources approaching the total maximum capacity of water resources in those areas and the cost continuously increasing, multiple systems of water reuse are appearing. Some industrial consumers are reusing treated water instead of the original fresh water. Developing water reuse has become an important measure for providing new water sources in China.

(b) China has rich sea-water and brackish-water resources. With the development of desalination, the decrease in desalination costs and the increase in costs of developing conventional water resources, desalination facilities have been established on some islands and some seriously water-short areas, which are expected to be developed and enlarged. China has a great potential and large market in developing desalination. Desalination will become an essential means to solving the problem of water shortages in areas which have rich resources of salt water.

(c) To develop non-conventional water resources, techniques suitable to the local conditions should be adopted, and attention must be paid to cheap wind power, solar energy and other local resources. Utilizing small-scale non-conventional water resources facilities can effectively meet the demand of dispersed rural households.

(d) Changes in the relationship between conventional and non-conventional water resources development must be actively followed; relevant techno-economic policies and regulations must be prepared; and a comprehensive system of water resources protection, development and utilization with a rational structure of water use must be established.

## D. Cyprus: Development of non-conventional water sources

by Savvas A. Theodosiou*

Cyprus is the second largest island in the Mediterranean Sea and lies at the eastern corner of that sea. It has an area of 3,570 sq. miles, is 300 miles long and 60 miles wide (see map 3). Sixty per cent of the whole island is arable, and the highest mountain is 1,961 m. Cyprus is a semi-arid country, with an average rainfall of about 500 mm, resulting in an annual average surface run-off of about 500 million $m^3$. Almost all rainfall falls within the winter months of December to February, while the rest of the year is sunny and dry, with maximum temperatures reaching 40°C in the central plains. The population of the island is about 650,000 people, 50 per cent of which is urban. Cyprus is traditionally an agricultural country but with light export-orientated industry and with thriving tourism, which is a very important source of foreign currency. The annual income per capita is $US 4,500.

### 1. Conventional water sources

Cyprus has a long history of irrigation which has been practised for over 2,000 years. Water for irrigation was conveyed in irrigation canals from springs, gravity chain-of-wells, river intakes and pumping from shallow wells by means of persian wheels or windmills. The first surface water storage works were constructed in 1896-1912 in the form of long low earth embankments. Up to 1950 surface water storage was not considered desirable for financial reasons, but after the early 1950s this policy changed and a number of small dams were constructed. However, it was only after 1961 that the big dam programme started. Up to 1960 the total water stored in dams was only 6.1 million $m^3$; today the total storage is 118.4 million $m^3$, and there are water works under construction that will double this storage by 1990.

The intensive effort to increase the surface water control and storage was considered inevitable because of the overexploitation of the ground-water aquifers, which were adversely affected by over-pumping.

Uncontrolled pumping had resulted in the depletion of some of the traditional inland aquifers and, even worse, caused sea-water intrusion into the coastal aquifers. It is estimated that there is an annual pumping from the aquifers of about 325 million $m^3$. The construction of water recharge works has helped to restore partly the state of some of the aquifers but for some the depletion is irreversible. The pumping of the coastal aquifers is now controlled by strict laws but, unfortunately, there is nothing that can be done to reverse the effects of sea intrusion.

There is an uneven geographic distribution of the conventional water sources: the west and south-west have most of the surface run-off, while the central plains are almost entirely dependent on ground-water aquifers. The east and south-east coastal areas are very poor in water resources.

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Map 3. Cyprus

## 2. Water use and demand

The annual water use in Cyprus today is estimated to be about 400 million $m^3$ for irrigation and over 30 million $m^3$ for domestic purposes; industry and mines use about 11 million $m^3$. Naturally, the amount of water used is limited by its availability. The availability of water resources limits the extent of land to be irrigated, on the one hand, and the per capita allocation of water for domestic purposes, on the other. Although the standard of living in Cyprus would require an amount of up to 230 litres per capita per day, today this is limited to about 150 litres per capita per day for the urban population and to less than 100 litres per head per day for the rural population. As regards irrigation, although the most modern techniques are used for saving water, only about 11 per cent of the cultivated land is under systematic irrigation because of the limitation of water resources. With the new major projects now under construction in Cyprus, the amount of irrigated land will be doubled but, even so, this is only a small fraction of the total cultivated land available.

It is thus clear that expansion of the land under irrigation and improvement in the domestic water supply to reach internationally-accepted levels would necessitate at least double the amount of water that is currently used. A simple water balance exercise thus indicates that, even if all the conventional water resources were to be fully utilized, they would not be sufficient to cover the rapidly increasing demand. It is estimated that the water that can be made available from the feasible exploitation of water resources is expected not to cover the demand after the year 2000.

## 3. Non-conventional water resources

The limitation of the conventional water resources and the appreciation that they would fail to meet the demand in the long run led the Government of Cyprus to the decision that alternative water resources would have to be investigated. It was then decided that three alternative water resources would be of immediate consideration: sea and brackish waters; reclamation of sewage; and cloud seeding.

### (a) Desalination

In the early 1960s the first large-scale desalination plants were installed in the Middle East for the production of drinking water, thus encouraging the Government of Cyprus to proceed with the study of that subject. Overseas consultants were called in and a number of feasibility studies were carried out, originally on the application of thermal distillation plants, either as dual purpose plants utilizing low-grade steam from power stations, or as single purpose plants. When these early studies were evaluated, it was clearly indicated that, compared with the cost of development of natural resources of corresponding yield, it was financially more attractive to develop conventional sources. With the further development of the island and the increased water demand for industry and tourism, other factors came into consideration outweighing the financial considerations, such as the higher quality of water needed for specific industrial applications in the food industry, beverages, chemical processes and so on. The development of the tourist industry started dictating its own terms, when the east and south-east coasts attracted tourist attention and were developed after 1974.

Since the area has very poor water resources, desalination was considered as an attractive proposition, and in such a case, cost was not the primary consideration. The Government then encouraged private investors to consider desalination as a new source of good quality water. However, its application was to be controlled by the Department of Water Development, so that proper arrangements would have to be made for the protection of the environment in order to safeguard the availability of the product. A number of tourist projects applied reverse osmosis for the treatment of brackish water, thus ensuring better quality water supply for their development.

With the development of reverse osmosis (RO) as a simpler and cheaper desalination process, new studies were undertaken by the Department of Water Development to assess its technical and financial applicability for Cyprus, both for large installations to provide for communities of up to 10,000 people, and also for tourist projects.

One of the more important projects undertaken by the Department of Water Development was one by which five RO modules, each using a different type of membrane, were obtained and mounted on trailers so that they could be moved to different locations easily. All modules were tested for three years at different locations for at least three months at each location. Each location was chosen so that the raw water would have a different quality e.g., high chlorides, high sulphides, excessive iron and also of differing concentrations. These experiments provided the Department with valuable information and experience on reverse osmosis. Two papers on the results of the experiments were presented at the international symposia held at Algero, Sardinia, and at Las Palmas, the Canary Islands.

In order to evaluate the various studies on desalination, carry out the experiments, follow the developments and control the implementation of desalination, the Department of Water Development formed a separate specialized section manned by qualified personnel in 1971.

From the studies carried out, it has been verified that up to the year 2000 the implementation of large plants for communal water supply or irrigation is not financially attractive. For the supply and installation of smaller size units in Cyprus, the costs of production from brackish water are estimated to be of the order of $US 0.93/$m^3$ and from sea water at $US 1.86/$m^3$. In Cyprus at present there are four thermal distillation plants and eight RO units.

The implementation of desalination in Cyprus has proved its usefulness as a new source of high-quality water, but also has shown that people tend to underestimate the importance of having properly-trained operators for proper running and maintenance. Almost all plants suffered loss of performance because of failure of the operators to run them properly due to lack of knowledge of the process. It is considered that proper commissioning is essential but, even more important, is to have properly-trained operators available from the start of operation of the plant.

(b) Sewage reclamation

Sewage treatment in Cyprus is a relatively new concept. Up to 1960 there were no sewage treatment plants in Cyprus, and sewage disposal was affected by soakaway pits. With the development of the island and the rising standard of living, sewage treatment became a necessity. The first developments to apply sewage treatment were large hotels on the coast and, at first, this was limited to primary treatment.

The results of the sewage treatment were very difficult to assess, as there was no official body or qualified engineers who could control the treatment plants. Subsequently, as the development proceeded, the Government decided that it was absolutely necessary to have properly-designed, constructed and controlled sewage systems that would cover the large urban cities and all the tourist projects.

For the large urban cities, feasibility studies were awarded to international consultants and by 1974 Nicosia and Famagusta were constructing sewage systems. Work is also currently underway for the design of sewage systems for the two other major cities of Limassol and Larnaca.

To control the sewage treatment of the scattered tourist projects all over the island, strict laws were passed by the Government, making it obligatory to treat all the sewage by conventional sewage treatment plants. Furthermore, the law restricted the disposal into the sea of any sewage, even of treated effluent, in order to control pollution of the beaches. The control of sewage treatment is now exercised by properly-manned services of the Ministry of Interior and the Department of Water Development.

The enforcement of the law for the control of sewage treatment and the desire to avoid any waste of water that could be made available guided the developers and the Government to promote the implementation of secondary or tertiary treatment of the sewage effluent, thus improving its quality to: $BOD_5$ below 20:30 and suspended solids preferably down to 15:15 or lower. With such quality of sewage effluent, there was an immediate use for the treated water in irrigation of the hotel gardens. Such an arrangement immediately made available for other uses the better quality water which had previously been used for irrigation.

The advantages of recycling of sewage effluent became apparent very quickly and, as a general principle, have been accepted and applied. At the same time, the danger to health of an uncontrolled use of sewage effluent has been clearly indicated, especially when it would be used for any agricultural purposes. As the use of effluent is a disputed subject, the Government decided to build its own experience and, for this, has restricted the use of sewage effluent to irrigation of gardens and permanent plantations for which the fruit is not eaten raw. Irrigation of vegetables is prohibited.

The Agriculture Institute of Cyprus is at present experimenting on the growing of cotton and animal foodstuffs with sewage effluent irrigation.

The recycling of sewage is expected to make available to Cyprus considerable additional quantities of water which will help to bridge the gap between the availability and demand of water.

(c) Cloud seeding

Cloud seeding appeared to be attractive during the late 1960s and some experiments were carried out by seeding the clouds with silver iodide crystals. The results were not only very difficult to assess, but also insignificant, so the experiments had to be abandoned.

## Conclusions

Of the non-conventional water resources considered for exploitation in Cyprus, only those provided by desalination for the production of high quality water for domestic and industrial use and sewage recycling for irrigation have so far proven to be of practical interest.

## E. Ethiopia: Some non-conventional water resource technologies

by Aseged Mammo*

### Introduction

This paper describes some of the relatively new methods of water supply and methods of identitying water resources that are being experimented with in Ethiopia.

Part 1 describes of the works of the Rural Pumping Technology Research and Development Project, being undertaken in collaboration with the Faculty of Technology, Addis Ababa University. Research topics include handpumps, wind-powered pumping and solar desalination. Project financing has been with assistance from the International Development Research Centre (IDRC) of Canada, SAREC of Sweden and previously UNDP/UNIDO.

Part 2 describes research and development work being undertaken in the Eastern Region of Ethiopia, with financial assistance from the Swedish International Development Agency (SIDA) and VIAK AB of Sweden as consulting engineers. Topics covered are remote sensing for water resources development, ground-water dams and shallow wells. No information was available on shallow wells.

The Ethiopian Water Works Construction Authority (EWWCA) of the National Water Resources Commission (NWRC) is the implementing agency for both projects.

### Background and justification

Ethiopia is a large country of 1.2 million km$^2$ with a population of 42 million. Some 90 per cent of the population live in scattered villages in rural areas, with agriculture as their major means of living. Of this huge rural population, perhaps five per cent have access to acceptably safe drinking water. After the International Drinking Water and Sanitation Decade, 1981-1990, Ethiopia has targetted that 100 per cent of the urban and 35 per cent of the rural population will have access to clean water. The average figure for developing countries was 30 per cent in 1980, which indicates the immensity of the job ahead in Ethiopia.

Like most developing countries, there is a severe shortage of trained manpower and funds in Ethiopia. Extensive use of low-cost systems that are dependent on local human and material resources are imperative for meaningful development in the water sector. Capital expenditures, especially those entailing foreign currency requirements for rural water supply systems, must be curtailed as far as possible. Simpler water supply techniques that minimize maintenance, operation and administrative problems need to be developed.

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It is, therefore, imperative that applied research towards producing equipment for use on rural water supply systems be accorded much greater attention than before. Study into eventual production of hand pumps, wind pumping equipment, and solar desalinators for brackish-water points, have thus been given priority.

Improvements in the techniques of selection of water resources and means of abstraction are also required, especially with respect to identifying and tapping the vast ground-water resources of the country. Use of ground-water dams is also unique to Ethiopia, but could have large potential, as many rivers are non-perennial. Research into these was also found necessary, and the associated costs were not very high.

The research into rural pumping equipment was essentially begun in 1974-1976, when all higher education in the country was curtailed in favour of field work. Staff and senior students of the Mechanical Engineering Department of the Addis Ababa University, engaged in research on low-cost water lifting devices, came up with a variety of designs which needed further investigation.

## 1. Rural Pumping Technology Research and Development Project

### (a) Handpumps

Handpumps are deemed essential in the extraction of water from hand-dug wells in the scattered villages of rural Ethiopia. The research project concentrated on piston pumps because they could easily be manufactured and maintained.

The project started out with five different designs, all of which were the result of the campaign mentioned above. Of these, one type was successful both in the field and laboratory tests. Later, this design was further sub-divided into two types - shallow and deep.

#### (i) Shallow well pump (Type BP50)

This is a direct action pump, employing no lever. It is simple and cheap to construct. It could serve at a maximum head of 10 m with a 50 mm nominal diameter plunger.

Originally its pump rod, cylinder and riser were all of poly-vinyl chloride (PVC) and the piston high density polyethylene, without any rings. The handle was wooden and clamped onto the PVC pump rod by friction. Pumping action is similar to a bicycle pump.

During tests at the Consumers' Association Laboratories in England, this pump completed 4,000 hours of endurance test without failure. However, early failures in the field due to abuse or incorrect well construction, and the local unavailability of some plastic components, have forced major design changes.

The new design employs a steel pump rod, handle and brass piston with leather cupseals. Cylinder material is still PVC especially made for the project, as the general PVC pipe produced in the market is not suitable for handpump use. The maximum pumping head has been reduced to some 8 m only.

(ii) Deep well (Type BPL)

This design is meant for heads of up to abount 30-40 m and employs a lever. The below-ground components are interchangeable with the shallow well design. The riser is made of galvanized steel pipe, as the threaded PVC riser failed early in fatigue loading.

Notable in the above-ground component is the use of nylon as bearing material. All other components are made from galvanized pipe and mild steel rods and sheets.

Field trials with this pump show that it must be built to withstand more abuse. A different design employing a hollow square section on a concrete pedestal is being adapted to economize on expensive steel.

(iii) Cost of handpumps

Handpumps so far have been made by the Research and Development Project using the Faculty machinery only. A strict pricing, therefore, has not yet been done. However, reasonable costs estimated so far are:

Type BP50 Birr 250 ($US 125) for a complete pump to 7 m.[1/]
Type BPL Birr 400 ($US 200) for a complete pump to 20 m.

These estimates are based on batch manufacture of 30 for Type BP50 and 15 for type BPL. The pump rod and riser costs considered are 14 Br m for both pumps.

The above prices are very reasonable as compared to imported units, which could cost as much as $US 500 (not including the riser). Although these imported units could have a somewhat longer life in the field, spare parts availability and low foreign currency requirements make the local pumps a better choice, especially at shallower pumping depths.

(iv) Observation

The handpumps have to be improved to withstand more abuse in the field. The biggest problem of the handpump programme so far has been maintenance. These units are numerous and scattered in villages with poor accessibility. A central crew from the government or other organization cannot handle the maintenance effectively.

The second phase of the research, therefore, concentrates on the training of the users (especially rural women) so that they themselves will be responsible for pump maintenance. When this is successful, mass production of handpumps will be completely justified.

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1/ $US1.00=Birr 2.07 (International Monetary Fund, International Financial Statistics 1986 yearbook, 1985 period average).

(b) Wind-powered pumping

Five types of prototypes were designed, built and field-tested by the project. Although they were primarily meant for borehole pumping for areas with sufficient wind, the 6 m and 7 m diameter prototypes were installed for irrigation. That was because no sites could be allocated in the project period.

It will also be noted below that for lack of proper laboratory facilities, some designs had to be altered after actual construction and field testing. The various types rotors, in increasing sizes, are described below.

(i) Filippini rotor

This vertical axis rotor has a 6 $m^2$ swept area and is installed for irrigation purposes. It employs hinged splitter plates which swing away by centrifugal force for speed control.

It drives a pair of 3-inch piston pumps at 2 m head, via a bell crank mechanism. A rotary pump would seem more appropriate for such a vertical axis machine. However, the cost of such a unit would be too high as compared to that of the wind mill - with an output of 390 W maximum.

Gross weight of the machine is about 400 kg and the estimated production cost was Br 2,500. The amount of material input into this rotor is much larger than that used in traditional horizontal axis mills of even larger outputs. Due to the large rotating mass, this design is not very suitable for manufacture in bigger sizes.

Other than trying a cheap and simple chain pump design that goes along with this rotor, the project has phased it out of the research programme.

(ii) Six metre diameter windmill

This wind turbine has three slender and large wooden main blades and a 2.8 m diameter multibladed starter rotor of galvanized steel sheet on the same shaft. It has a tip speed ratio of 1:4.7 and rotor speed of maximum 120 revolutions per minute (RPM).

Speed was originally controlled by the use of tip-flap spoilers. However, as this system did not function well in the field, a centrifugal pump was manufactured and coupled with it, because it would load the rotor progressively more as the wind speed increases.

During field tests, however, the mill delivered more than 20 l/sec at 2 m pumping head for a few minutes. The lightly built rotor continued to speed up, however, and failed at the hub due to overspeed and subsequent vibration.

A conventional tail vane for control and orientation at a lower tip speed ratio, along with a set of new blades, has been fitted. Its rated power is 2.17 KW at 8 m/s wind speed. Gross weight of the machine is 800 kg with an estimated production cost of Br 5,000.

(iii) Seven metre diameter windmill

This moderate speed prototype (tip speed ratio of 1:2.8) consists of 6 wooden blades and classical tail vane orientation and control. It has been used for irrigation since March 1982 and supplies about 200 $m^3$ per day at 2 m pumping head with four piston pumps. A matched centrifugal pump would easily deliver 700 $m^3$/day, considering the favourable wind conditions at the site. Since this unit has been performing well in the field, another one has already been manufactured and installed near Dire Dawa. It is rated at 2.8 KW at 8 m/s wind speed. Its gross weight is 1,100 kg with an estimated production cost of Br 7,000.

(iv) Nine metre diameter windmill

This prototype has three fixed main blades and another three relatively shorter and broader starter/control blades. It is installed at a borehole with a pumping head of 50 m driving a mono pump via a bevel gear box at the millhead, a centrifugal clutch at the vertical shaft and another bevel gear box before the pump drive head.

Speed control is effected through flyweights actuated by centrifugal forces acting on the starter/control blades and synchronized by a simple star mechanism. The starter/control blades are set at comparatively larger angles ($30^o$) to facilitate starting and could be turned up to $-30^o$ during operation by the flyweights for braking.

It has a tip-speed ratio of 1:5.7 with maximum 90 RPM. Its rated power is 5 KW at 8 m/s wind speed. Its gross weight is 1,250 kg with an estimated production cost of about Br 8,000.

(v) Ten meter diameter windmill

This is the largest prototype the research project has made so far. It uses six fully feathering wooden blades, synchronized by a single bevel gear mounted on the rotor shaft and with a pinion on each blade shaft. Actuation is flyweight controlled, and restoration with a centrally mounted single spiral spring.

During design it was estimated that the rotor would produce enough starting torque to drive the mono pump at a cut in wind speed of 3 m/s. However, dynamometer tests showed the need for a friction clutch, and one was made and installed. A step up ratio of 16 is used between rotor and pump, via a bevel gear pair at the millhead and a double v-belt drive. Positioning of the heavy clutch at the high speed side (for lower torque and higher life) has created numerous technical difficulties ever since commissioning.

This prototype is also installed for borehole pumping head of approximately 50 m and an output of 8 KW at the rated wind speed of 8 m/s. Its gross weight is 1,200 kg with an estimated production cost of about Br 10,000.

(vi) Recommendations and conclusions

After a considerable length of field testing of windmills, the research group recommends the following:

(1) All windmills must have a speed control mechanism. The types found satisfactory are:

- Classical tail vane orientation and control for sizes up to 7 m.

- Simple star synchronizer - similar to one used on 9 m design for larger sizes.

(2) Diameters 7 m and 10 m could be used for bulk manufacture.

(3) Further investigation is required into:

- Wind data for wind power harnessing, as existing information in Ethiopia is primarily for aviation and agricultural purposes. Low average speed does not necessarily mean no higher wind speeds for shorter periods.

- High solidity ratio mills to cover low wind speeds of less than 3 m/s. This is despite its higher material costs.

- Glass reinforced plastics for the manufacture of larger rotors, as longer wooden blades are not available.

(4) Although detailed costing of windmills has not been made, indications are that locally-produced units are highly competitive in price with imported ones.

(5) Despite the fact that average wind speeds are quite low in many parts of Ethiopia, wind power harnessing has good potential for irrigation and domestic water supply.

(c) Solar Desalination

Ground water is brackish in many parts of eastern and southern Ethiopia and along the Red Sea coast. These areas are regarded as arid or semi-arid and are relatively sparsely populated. Development in these areas must be preceded by the supply of potable water. Because of the availability of abundant sunshine in those areas, solar desalination seems to be an appropriate solution, and has therefore, been added in the research programme.

Standard solar stills, employing glass covers are fragile and expensive, with costs for 3 mm glass at about 40 Br/$m^2$ in Ethiopia. It was decided to use little or no glass in the designs.

Figures 38 and 39 show two prototypes built by the project. The design in figure 38 was chosen because of its reputed high output of 10 l/$m^3$/day (Seufert, 1978). A 2 $m^2$ prototype was built, with a long chimney to create a natural draft. There was practically no distillation.

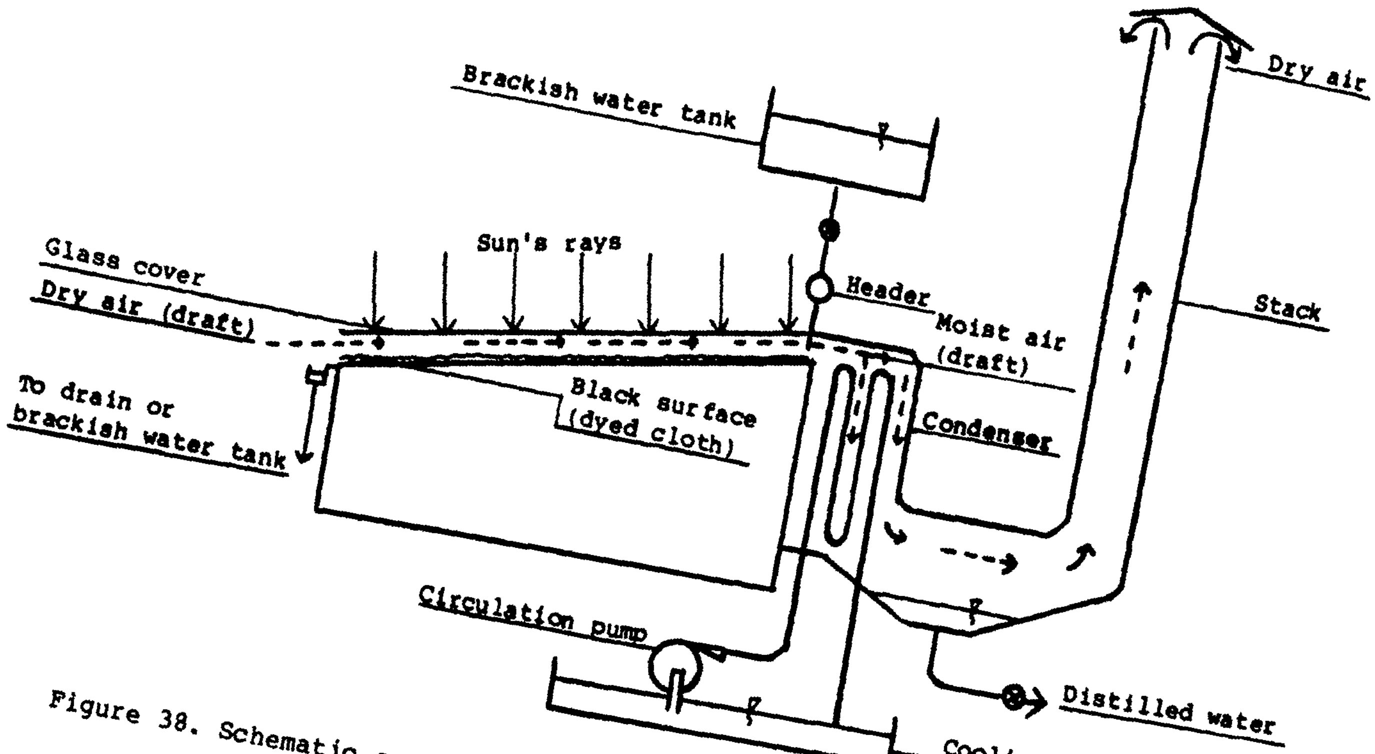


Figure 38. Schematic outline of a solar moist air desalination prototype

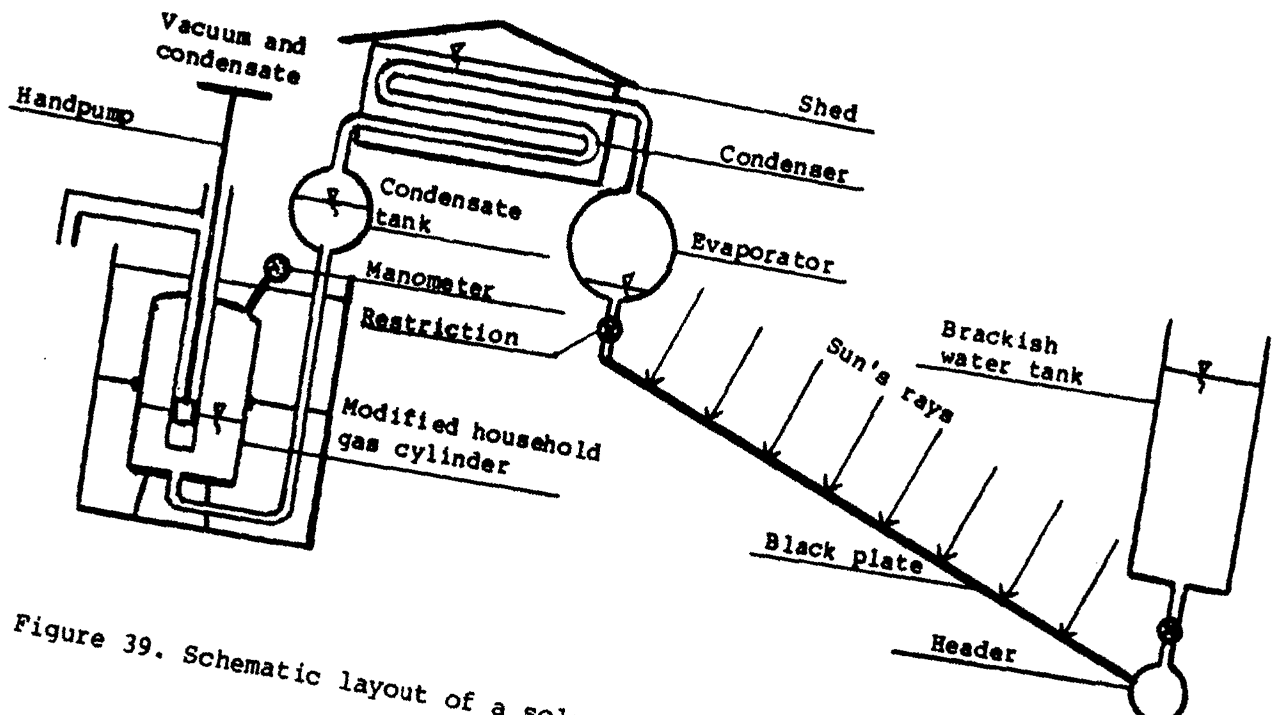


Figure 39. Schematic layout of a solar flash boiling desalinator prototype

Although poor sealing in the condenser and between glass and adjacent desalinator body could lower efficiency of the unit, a more important cause for the failure of the unit was insufficient air draft.

The design shown in figure 39 (the flash boiling desalinator) was constructed after the earlier prototype failed. A handpump acts as a combined pump and condensate pump. It created the high vacuum of 97 per cent (17 mm Hg) when tested alone, and could maintain it for a long time as it was submerged in water (no air infiltration).

It is hoped this desalinator prototype will create and maintain a high vacuum in the system and thereby considerably lower the boiling point (BP) of water (BP of water at 17 mm Hg = 20$^{o}$c). The output should be high, especially since it should even work when there is no direct sun. The major anticipated problem is air in the system. The high vacuum may not be maintained because of air leakage into the system, or air dissolved in the water. The vacuum pump and condenser are always under water.

So far, the maximum vacuum to be created in the system has been about 70 per cent only. Leak points are being detected.

2. Research and development work being carried out with Swedish assistance

(a) Remote sensing for water resources development

The Ethiopian Water Works Construction Authority, in cooperation with the Swedish International Development Agency (SIDA) and VIAK AB of Sweden as consultants went into a demonstration and training study of remote sensing for use of satellite imageries for water resources exploration. The project was carried out between 1983 and 1984.

The research project covered an area of 5,500 km$^2$ around Dire Dawa, Eastern Ethiopia, out of a total area of 34,000 km$^2$ covered by the imagery. The area chosen has few perennial rivers, frequent drought and ground water the main source for domestic water.

It is hoped that results from this test area could be used for similar regions elsewhere in the country. Use of relatively simple instruments, which already existed in the country, was also a major consideration of the programme.

The climate in Ethiopia is distinctly wet and dry. The project thus studied imageries from both wet and dry seasons (multitemporal). Imageries from the dry season gave good information on less season-dependent or static elements (drainage patterns. alignments and land forms). Those from the wet season gave better information on the season-dependent or dynamic elements (drainage conditions, vegetation and land use).

Mapping of the six terrain elements essential for the hydrological evaluation was performed at the rate of 140 km$^2$/hr. For a fully geometrically corrected Landstat multi-spectral scanning (MSS) scene, the mapping rate could be increased to approximately 200 km$^2$/hr, because of limited degrees of variation only in the terrain.

The cost of images, mapping analysis and geo-hydrological evaluation for the project has been calculated at less than 2 $Br/km^2$ for the test area of 5,500 $km^2$. If a complete Landsat scene of 31,450 $km^2$ were to have been studied, the cost would have decreased to well below 1 $Br/km^2$. Thus, there is clearly documented scale advantage in a regional study based on Landsat images.

If the same project were to have been based on aerial photo interpretation, it is estimated that the cost would have been 50 per cent higher for the test area and nearly three times as high for a full Landsat scene area.

Further technical details are beyond the scope of this paper. Reference could be made, however, to the Final Report of the project, Remote Sensing for Water Resources Development, prepared for the Provisional Military Government of Socialist Ethiopia, by VIAK Consulting Engineers, 1984.

Visual analysis of Landsat multi-spectral scanning images from a dry and a wet season studied in a stereoplotter allowing accurate transfer of information onto a base map, has been shown to be a reliable, simple and cost effective method for making general synoptic terrain inventories.

The techniques involved are simple and could be applied by professionals, after a short period of training. Equipment used was what was already in Ethiopia, and normally used for conventional topographic mapping. It is also suggested that initial efforts, at least, should be in co-operation with the Ethiopian Mapping Agency.

(b) Ground-water dams

Rain falls in most of Ethiopia in the form of storms, i.e., it may fall heavily in an area for a few weeks while the rest of the year is dry. Consequently, areas with an annual precipitation below 800 mm are regarded as arid in Ethiopia (Mariam, 1984). Ground-water dams, therefore, could be applicable to many parts of rural Ethiopia (Hanson and Nilsson, 1984; Claesson and Ljung, 1985). The two types of dams are: sub-surface dams, constructed below ground level to arrest the flow in a natural acquifer; and sand storage dams, structures that impound water in the sediments caused to accumulate by the dam itself.

The idea, however, is new to Ethiopia and, as such, demands more experiments with different geological conditions, designs, and locally available materials before large scale adoption. Eastern Ethiopia is one such region which has potential for ground-water dams, and along with studies into remote sensing, it was chosen for the research project.

These dams have the advantages over conventional surface dams in that they have:

(i) Low construction costs compared to a surface dam;

(ii) Reduced evaporation and silting, as they are already filled with sediments;

(iii) Better water quality than a surface dam.

(i) Selected dam sites

A total of six sites were selected with the aim of using the water for domestic purposes and irrigation. The dams at Bombas and Gursum were built earlier (1981) by the United Nations Children's Fund (UNICEF) and EWWCA.

Gande Balina. There is no sub-surface flow in the river sediments during the dry season. The dam built is about 1 m above the surface of the riverbed to create ample storage for use in the surrounding villages.

After completion of the dam, however, there was no water collected behind the dam. The probable cause of failure in the first place, was a fissure in the bedrock, as the site is in a fault zone. This crack could not be seen, and as there have not been sufficient floods since its completion, it is not known if the crack will fill up. Also the catchment area for the dam appears now to be too small.

The foundation of the masonry wall has since been built deeper into the bedrock, in order to minimize leaks. A large crack has also been discovered under the sand in the upstream side and was filled with cement slurry. The next rains and flood will verify if the repair work was sufficient.

Eja Anani. The dam at this site is of a totally submerged design and could gradually be raised if demand for irrigation water increased. After the dam was partially constructed in the traditionally dry season, unexpected rains and subsequent floods washed down the whole thing. Work has to start over from the beginning as soon as crews are finished with the other sites.

Melka Jebdu. This could be regarded as a combined sub-surface dam and spring development scheme. By building a sub-surface dam some 10 m downstream of the spring capping constructed by the project, the entire sub-surface flow in the river is collected and used for irrigation of orchards, the town supply (pop. 2,500) and cattle trough. Because of the high sub-surface flow at this site, storage created behind this dam is of little importance.

At commissioning (March 1985), the scheme included the subsurface dam, two capped wells, one water point with eight faucets, a cattle trough, and an output of about 6 l/s. Total cost was just over $US 20,000.

Kore. This sand storage dam is of a totally submerged design, with plastered stone masonry 6.7 m high, 25 m long and thickness varying between 2 m at the bottom to 1.2 m at the top. The dam supplies the town of 1,500 with potable water with discharge of 3.5 l/s and was commissioned in March 1985. The total cost of the scheme (dam, public fountain, capped well and piping work to the fountain) was $US 20,000.

Bombas. This sub-surface dam was built in 1981 by EWWCA with aid from UNICEF. The crystalline bedrock concrete blocks rose 0.8 m above the original sand surface. The original stone mansonry for erosion protection partly collapsed and the trench for the dam was filled once with sand after unexpected rains and flood during construction. Also, there should be an overflow in the dam wall which would prevent the water table from rising to the surface and thus minimize the risks of pollution. Project cost was $US 15,000.

Gursum. This unique sub-surface dam was also built by EWWCA and UNICEF in 1981. The material behind the dam is silt and clay (no sand) with low permeability. A 200 $m^3$ excavation with plastered stone masonry was thus made and covered with a concrete roof resting on concrete columns. Water from a nearby spring was also diverted into the reservoir. The scheme supplies the town of 5,000 inhabitants with potable water and cost US$ 150,000.

There are other ground water dams planned for Bisidimo and Kamarro, but construction has not begun because of technical difficulties (the Bisidimo catchment area is in excess of 900 $km^2$). Both sites may be left out altogether.

(ii) Recommendations

(1) Site selection for a sub-surface dam has to be done carefully and thoroughly because the hydrogeological conditions, i.e., quality and quantity of sand, clay, bedrock, catchment area have to be considered.

(2) Construction has to be swift and well planned to avoid unforeseen floods.

(3) Despite its simple construction, preventive maintenance in a ground water dam should not be neglected.

(4) The cost of a subsurface dam is reasonable, provided it is built successfully the first time, and should be considered in areas where other conventional methods cannot be arranged.

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## F. Indonesia: The use of non-conventional water resources

by Badruddin Mahbub*

### Introduction

Non-conventional water resources are used in some areas in Indonesia as the option when conventional resources are not available. Such resources have been explored traditionally by the people living in rural areas as well as in urban area. In this connection, there are two kinds of activities which are reported in this paper: rain-water collection for potable water; and the reuse of domestic waste water for the irrigation of rice fields and fish ponds. This latter technology is very useful in solving environmental problems in urban areas as well as increasing rice production in the rural areas.

Research and development of rural water supply have been undertaken by governmental institutions as well as active community organizations. Activities have included: the treatment of river water with Moringa Oleifera seed; and the treatment of peat water with local clay containing halotrichite.

Recent developments in weather modification to increase precipitation in the dry season are also reported in this paper.

### 1. Collecting rain water for potable use

Rain water is collected for potable use by Indonesians living where fresh water is difficult to find. The plains of Kalimantan suffer from saline water intrusion every dry monsoon, even several tens of kilometres inland. The same problem occurs in the irrigated rice-growing areas in Sumatera. In Java, rain water is collected by the people living far from fresh water sources, such as Gunung Kidul (Central Java), and along the north coast where fresh water is almost unavailable in the dry monsoon. Here, developing rain water collection systems is relatively new compared with Kalimantan, where such systems have been widely applied, not only by the rural population, but by urban people as well, because fresh water supply from the municipal service cannot meet the demand.

There are a number of technologies for collecting rain water for potable use, namely:

(a) Iron drums (200 l) much used in the transmigration areas of Sumatera.

(b) Wooden tanks (1,000 - 1,500 l) widely used by Kalimantan people, made in a traditional way in the past, but now replaced by ferro-cement and fibreglass products.

(c) Concrete tanks of 2 - 5 $m^3$ capacity.

(d) Ferro-cement tanks (200 - 1,000 l) for one, or for a number of families (10 - 25 $m^3$).

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(e) Bamboo cement vessels to serve several families (5 - 10 $m^3$).

(f) Fibreglass tanks (500 - 1,000 l).

The rainfall is caught directly from house roofs, flows through flumes into the reservoir, and is used without treatment. For potable use, the rain water has to be boiled first. Several technologies have been developed to treat rain water collected from house roofs using sand filter systems:

(a) Tanks of 10 $m^3$ capacity provided with a rapid sand filter (figures 40 and 41). The pilot plant was developed by the Rural Water Supply Project, Ministry of Public Health, with the aid of the Netherlands Government.

(b) Cistern with slow sand filter, having a holding capacity of 15 $m^3$ and a filter area of 8 $m^2$ (figure 42). The pilot plant was developed by the Institute of Hydraulic Engineering, Ministry of Public Works, aided by the Government of the Federal Republic of Germany.

A comparison of costs of the various types is shown in table 56. For households, people tend to choose the cheapest and simplest types. For a group of houses or a school, a more sophisticated system may be used.

Since 1979, Indonesia has constructed 23,500 rain-water collectors, capacity 10 $m^3$, thoughout villages in all provinces. Their average cost is $US 400 and the total investment is almost $US 10 million.

## 2. Purification of peat water for potable use

People living in swampy areas of Kalimantan have difficulty finding potable water; river and canal water is generally dark brown due to high humus content. In addition, the pH is quite low and it is difficult chemically to treat the water conventionally, and impossible at village level.

Since 1982, the Institute of Building Research, Ministry of Public Works, has investigated the possibility of purifying peat water for potable use using a locally available absorbent mineral and coagulant, peat clay which contains halotrichite. Such a peat water purification system is currently being developed on a household scale to treat 200 l of water, requiring 500 grams of peat clay, and a coagulation time of 5 to 10 minutes, settling time of 45 to 60 minutes. Then, water is passed through a sand filter that costs $US 50 (see figure 43). The data on the quality of the treated peat water (table 57) indicates that this method is very effective in reducing the colour and organic matter content, and in raising pH to neutral.

## 3. Purification of river water using Moringa Oleifera seed

River water can be purified by a coagulant derived from plants, as developed by DIAN DESA (an Indonesian autoactive community organization), using Moringa Oleifera seed. This treatment has been applied by the rural population in Java; raw water containing 6,200 mg/l suspended solids is treated by the seed to obtain clear water containing 20 mg/l suspended solids without filtration. The seed has the ability to coagulate mud, and to reduce

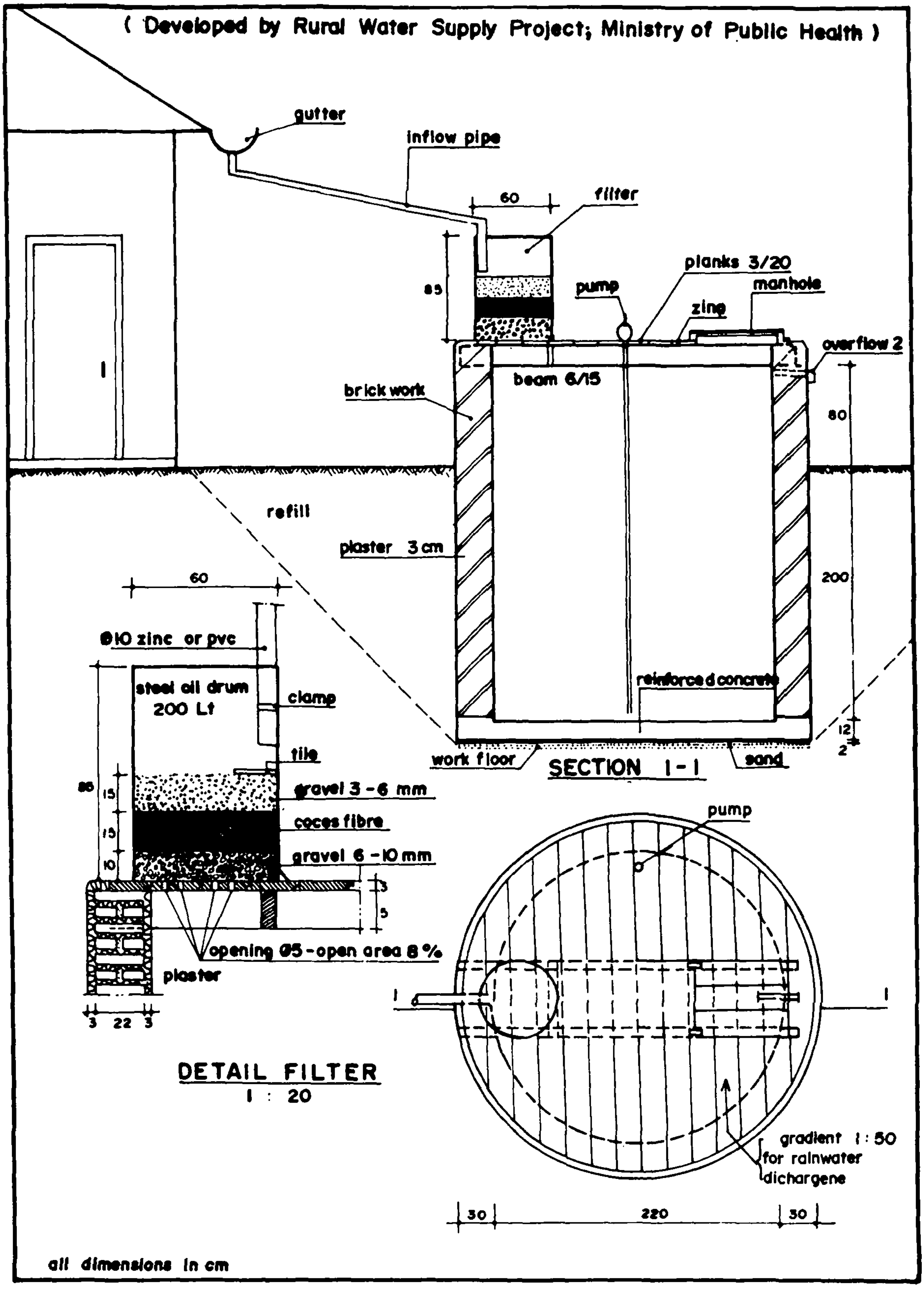



Figure 40. Brickwork rain-water collector (10 $m^3$)

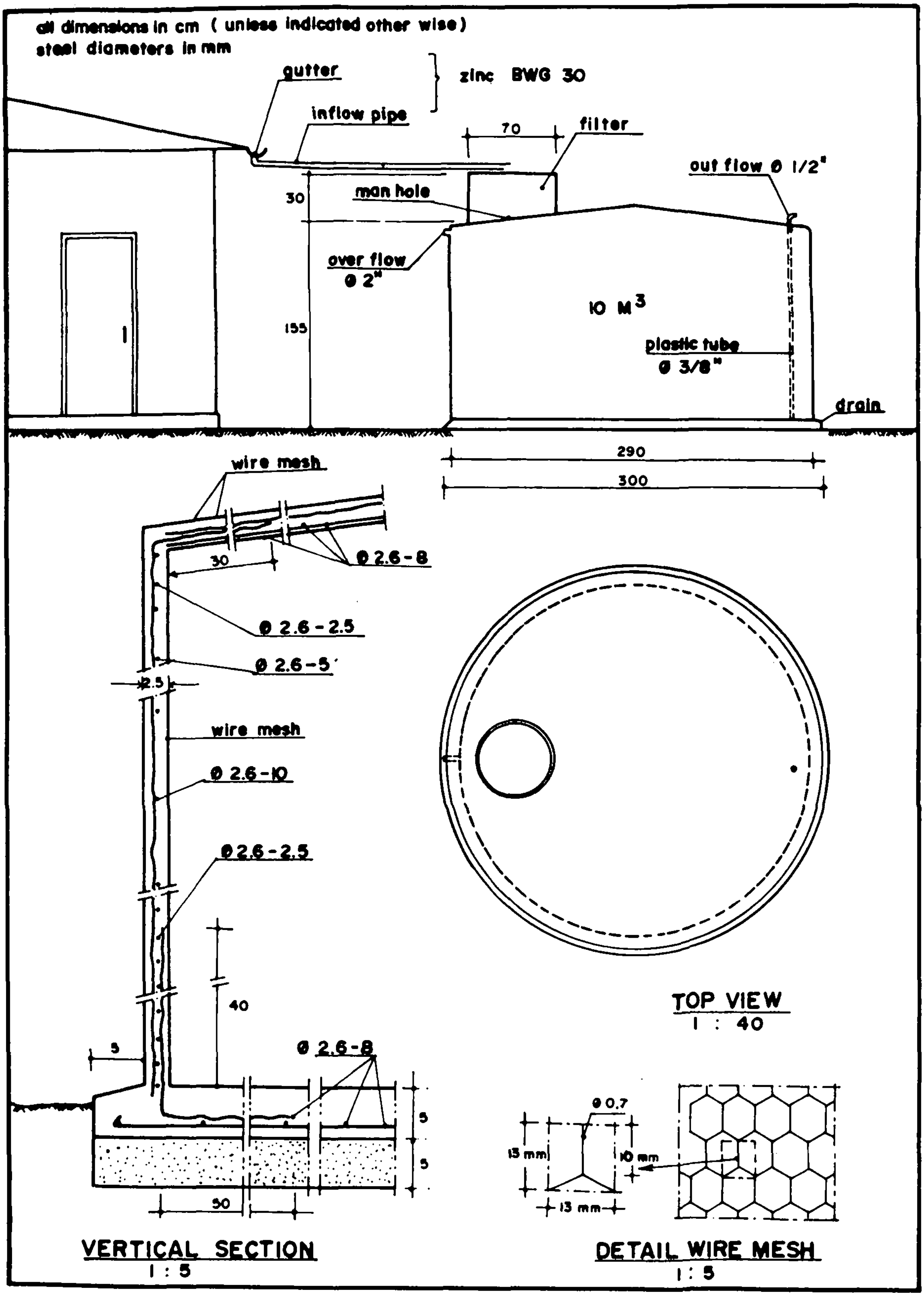
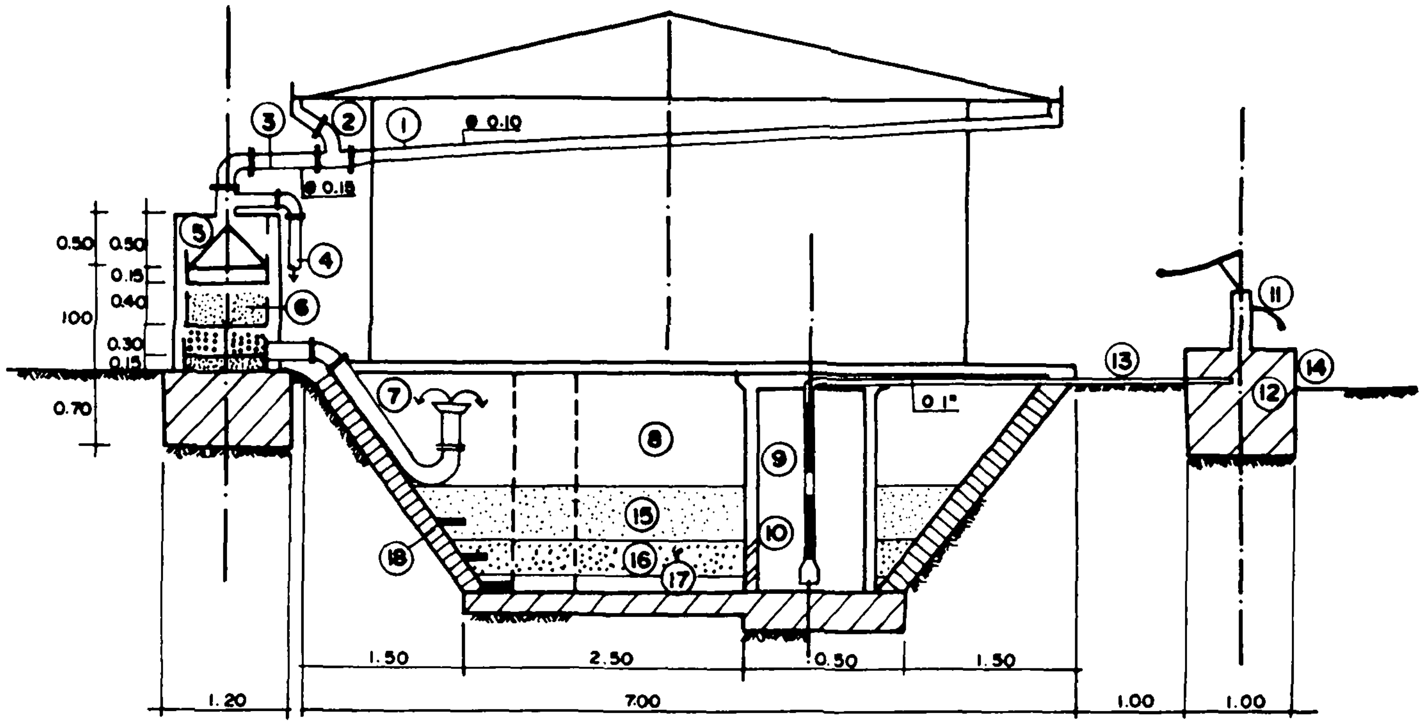



Figure 41. Ferro-cement rain-water tanks (10 $m^3$)

**( Developed by Rural Water Supply Project; Ministry of Public Health )**




( Developed by The Institute of Hydraulic Engineering; Ministry of Public Works )

LEGEND :

Scale 1 : 65

1,2 Plastic tube gutter ø 100 mm
3 Slide plate
4 Rain overflow
5 Cone for rain water distribution
6 Sand filter
7 Pipe for rain water introduction
8 Cistern
9 Catch basin
10 Holes
11 Pump
12 Foundation for the pump
13 Suction pipe
14 Tiles
15 Sand
16 Gravel
17 Stone
18 Iron steps

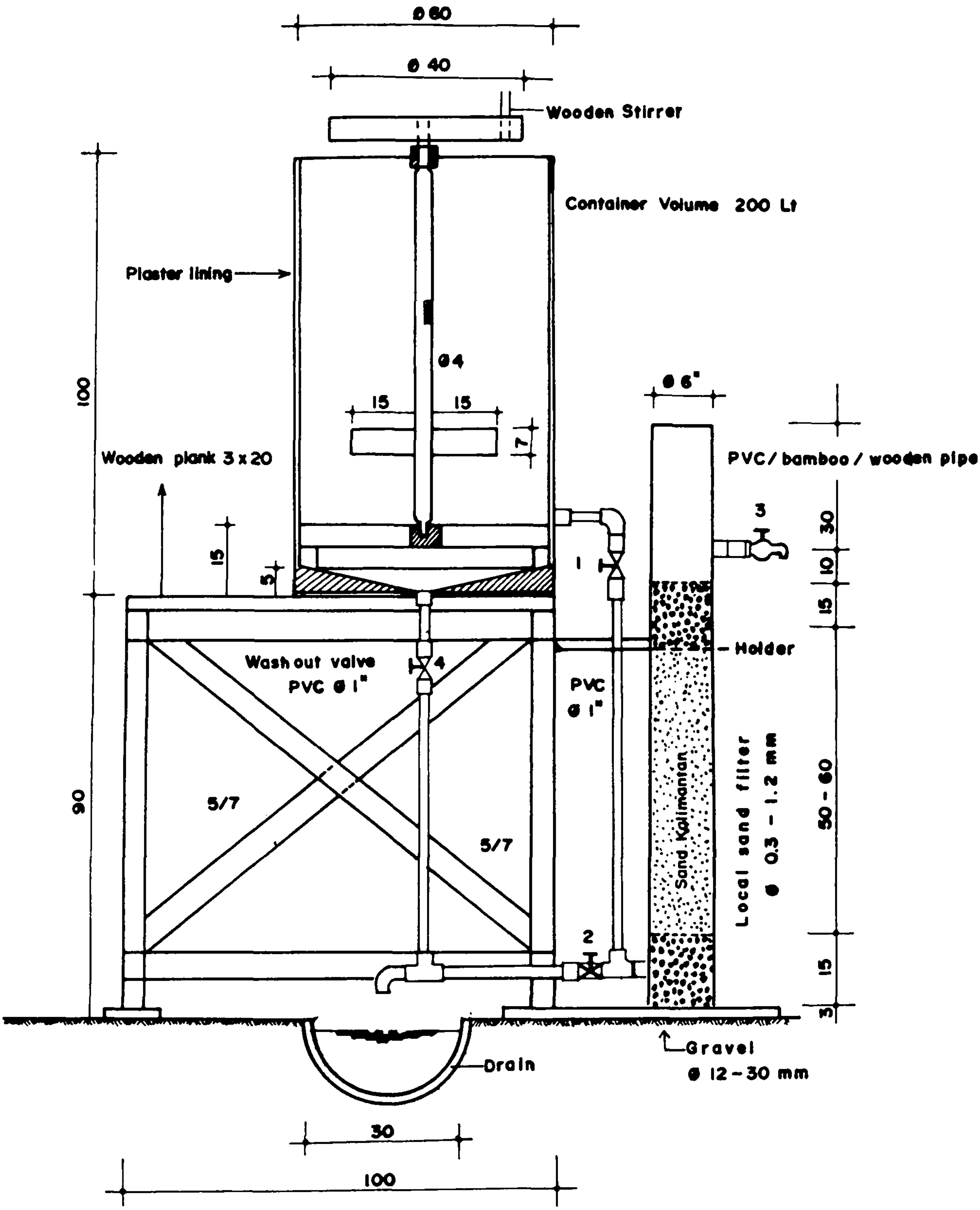
Figure 42. Cistern with slow sand filtration, Ciburial, Indonesia

Table 56. Comparison of several technologies of rain-water collection for potable use

| Type | Capacity ($m^3$) | Service (drinking water) | Materials of construction | Cost ($US) |
|---|---|---|---|---|
| Drum | 0.2 | 1 family | iron | 5 |
| Big jar | 0.2 | 1 family | ferro-cement | 25 |
| | 1.0 | 1 family | ferro-cement | |
| Cylindric vessel | 1 - 1.5 | 1 family | iron/wood | 100 |
| Vessel | 0.5 | 1 family | fibreglass | 50 |
| | 1.0 | 1 family | fibreglass | 70 |
| Vessel with rapid sand filter | 10 | 20 people | ferro-cement | 150 |
| | | | brick | 250 |
| | | | concrete | 700 |
| Cistern and slow sand filter | 15 | 60 people | brick | 2,000 |
| Dug well and pressure filter | 10 | 1 family (drinking, bathing, washing, toilet) | concrete well, sand filter in iron cylinder electric pump | 500 |

Table 57. The quality of peat water

| Parameter | Before treatment | After treatment (Doses of clay: 625 mg/l) |
|---|---|---|
| Colour (PtCo Unit) | 903 | 11 |
| Turbidity (mg/l $SiO_2$) | 30 | 0 |
| pH | 4.5 | 7.3 |
| Organic Matter (mg/l $KMnO_4$) | 245 | 13 |




**( Developed by The Institute of Building Research; Ministry of Public Works)**

Figure 43. Model of an individual peat water treatment installation

the number of bacteria in the water. A dose of 1 ground seed is sufficient to clear 1 litre of water in 3 hours and to destroy 90 per cent of the coli bacteria in 20 minutes. The Institute of Building Research has used the seed to treat peat water, and taking a dose of 20 seeds per litre, the dark brown colour can be cleared; however, the organic matter content in the water remains high.

Table 58 shows the quality of peat water before and after treatment with Moringa Oleifera seed powder.

Table 58. The quality of peat water after treatment with Moringa Oleifera seed

| Parameter | Raw water | Treated water |
|---|---|---|
| Colour (PtCo Unit) | 904 | 15 |
| Turbidity (mg/l $SiO_2$) | 30 | 0 |
| pH | 4.53 | 6.95 |
| Iron (mg/l Fe) | 1.20 | 0 |
| Organic Matter (mg/l $KMnO_4$) | 150 | 110 |

Source: Institute of Building Research, Ministry of Public Works, Indonesia.

## 4. Weather modification (cloud seeding)

Indonesia is a tropical country having a high rainfall, but the distribution is variable. Even in regions where the rainfall is high, a drought may occur during a long dry monsoon. Weather modification technology by cloud seeding is being developed by the Institute for Study and Application of Technology, Ministry of Research and Technology, which has been conducting various experiments and applications since 1977. The main objectives are to protect agricultural production from drought (experiment on the island of Lombok in 1977), to increase the harvest by making the cropping pattern more efficient and to augment water storage for the benefit of a hydroelectric power station during the dry monsoon (experiments carried out over the Jatiluhur reservoir catchment area in 1979, 1980 and 1981).

Cloud seeding has used hygroscopic chemical seed shot into the clouds so that a condensation process occurs and rainfall is the result. Hygroscopic particles of salt (NaCl) and calcium chloride ($CaCl_2$) in the form of fine powder 10 - 50 microns in size, are used as seed and sprayed by airplanes producing the nuclei of rain particles which are further developed by spraying urea.

The advantages of weather modification are considerable, since at a relatively low cost, high production and benefits can be achieved. Tests conducted over the Jatiluhur reservoir area indicated that the water produced by weather modification cost only \$US 5/1,000 $m^3$. One test in November 1979 produced 118 million $m^3$ which was able to increase the yield of 55,000 ha of rice fields by \$US23 million, and to increase the generating power of the hydroelectric power station to 23.6 million kWh, a gain of \$US 472,000.

## 5. Reuse of waste water for irrigation

Domestic waste water is not only a source of pollution but also contains nutrient elements such as nitrogen and phosphorous which are useful for agricultural purposes. While people living in rural areas have applied the principle of recycling waste water for fish ponds and gardening, such ideas have not yet been applied in the urban areas. However, it was found by the Institute of Hydraulic Engineering (IHE), Ministry of Public Works, that the irrigation network which received the raw water from the rivers flowing through Bandung, produced high yields of rice, even without the addition of artificial fertilizer.

The rivers received the domestic waste water from almost 1.5 million people of Bandung, and then irrigated 2,500 ha of rice fields and fish ponds. Table 59 shows the characteristics of domestic waste water, containing, among others, total nitrogen of 11 g/person/day and total phosphorous of 1 g/person/day. If compared with the specifications for regular fertilizer, i.e., 200 kg Urea, 100 kg triple super phosphate (TSP) and 100 kg Potassium sulphate (ZK) for each hectare of rice field for the four month crop season, the average use of nitrogen is 770 g/ha/day, and of phosphorous 182 g/ha/day. Thus, the waste from approximately 200 people has the potential to fertilize 1 ha of rice field.

Table 59 The composition of domestic waste water in Bandung, Indonesia

| Parameter | Content (g/capita/day) |
|---|---|
| BOD | 25 |
| COD | 57 |
| $NH_3$-N | 1.83 |
| $NO_2$-N | 0.006 |
| $NO_3$-N | 0.97 |
| Organic - N | 8.3 |
| Total - N | 11.1 |
| Total - P | 1.1 |
| Detergent as MBAS | 0.63 |
| Phenol | 0.006 |
| Faecal coli (number/capita/day) | $14 \times 10^{12}$ |

Even though such a recycling operation has gone on without engineering planning since the beginning, it can be concluded that, with adequate dilution, the reuse of domestic waste water from urban areas for irrigation is appropriate for development and application in tropical countries. The IHE is now starting to investigate the possibility of applying this technology more widely in Indonesia, and a pilot scheme is under preparation.

## 6. Possibility of developing an integrated system of urban sanitation and irrigated development

Providing sanitation services for human settlements, particularly control of water pollution due to domestic waste water, is a heavy and expensive endeavour.

It is difficult to choose among the various technologies for domestic waste water purification. Among the conventional technologies, the highly efficient sophisticated technology requires a high level of skill and operation, as well as high investment and operation costs. More simple technologies with low operating costs, such as lagoons, require a vast area of land, which is very expensive in the urban and suburban areas of Java. Moreover, testing and application of the technology is required, as well as experience and skill.

Nevertheless, on the basis of experience in Indonesia and data from the Bandung area, reuse of domestic waste water may be applied as irrigation water for the rice fields, so as to develop an integrated system for urban sanitation by means of an irrigation network. Towns having rice fields downstream, with a topography sloping towards the rice fields are more suitable for application of the system.

The case study in Bandung supports the possibility of applying the repeat cycle process. However, further investigation of the study area is needed.

Conclusions reached so far on the basis of data from the Bandung case study are as follows:

(a) Pre-treatment of domestic waste water is essential prior to sending it into the irrigation network. A retaining pond with a 48 hour retention time and a depth of 1 m is sufficient to kill 90 per cent of E. Coli bacteria originating from faeces, while 72 hours is sufficient to kill 99 per cent.

(b) To prevent an excessive amount of nitrogen coming into the rice fields, control of dilution of domestic waste water for irrigation is necessary so that an optimal cultivation of rice fields without using fertilizers will be achieved, particularly during the generative phase. A total content of 15 ppm of N indicates a fairly good paddy growth and yield. This rate of content can be achieved by an irrigation water ratio of 0.8 $m^3/s$ for each 100,000 people, so that it is suitable for irrigation on 800 hectares of rice fields.

(c) Control of people's health should be established, especially of the farmers tilling the rice fields, as they are in direct contact with water that still contains a high amount of bacteria.

## G. Turks and Caicos Islands: Brief notes on water supplies

by K.F. Sparkes*

In the Turks and Caicos Islands, a small British Crown Colony at the south-eastern extemity of the Bahamas archipelago (map 4), all water supplies are non-conventional.

The climate is Trade Wind tropical and dry; the land low-lying and fragmented; the Pleistocene colitic limestones and Holocene sands generally very permeable. As a consequence there is no surface fresh water, and salt water underlies all the land; only in a few scattered favourable locations does rain water percolate downwards from stable, but small, Ghyben-Herzberg lenses of abstractable fresh ground water.

For hydrological and indeed for other purposes, the components of the group fall into two categories:

(a) The Salt Islands: Grand Turk (the capital); South Caicos; Salt Cay; West Caicos, Amergris and other remote Cays.

(b) The Lower Caicos Islands: Providenciales; North Caicos; Middle Caicos; East Caicos, Pine Cay, Parrot Cay and the small Cays lying between North Caicos and Providenciales.

The main islands of the first group are relatively small and, under the original natural conditions, contained extensive shallow ponds and swales; the dry climate, and evaporation much in excess of annual rainfall, cause such inland waters to become very saline in the dry season and for salt to precipitate out along the drying edges. In the 18th and 19th centuries, North American demands for salt as a good preservative led to the conversion of these shallow waters into intensively managed systems of walled ponds or salinas, supply canals and wind-pumping arrangements together with collection, storage, packing and ship lightering facilities.

Everything was oriented towards the manufacture and export of a single, high value and readily marketable product so, in essence, it was a very typical early-modern industrial society: a large number of relatively low-paid unskilled and semi-skilled labourers with a few relatively wealthy proprietors --or at least the latter hoped to be when the heavy initial costs of the fixed assets had eventually been paid off.

In fact, following the enormous demand for salt to preserve meat for troops in the American Civil War, the industry has been, apart from an occasional flurry, in a continuous decline because of competition from more economic, large, land-based operations elsewhere. By the end of World War II Government subsidy became necessary, and all operations finally ceased in the early 1970s. What has emerged is the classic case of a completely urban society faced with the collapse of the sole industry which was the reason for its existence in the first place.

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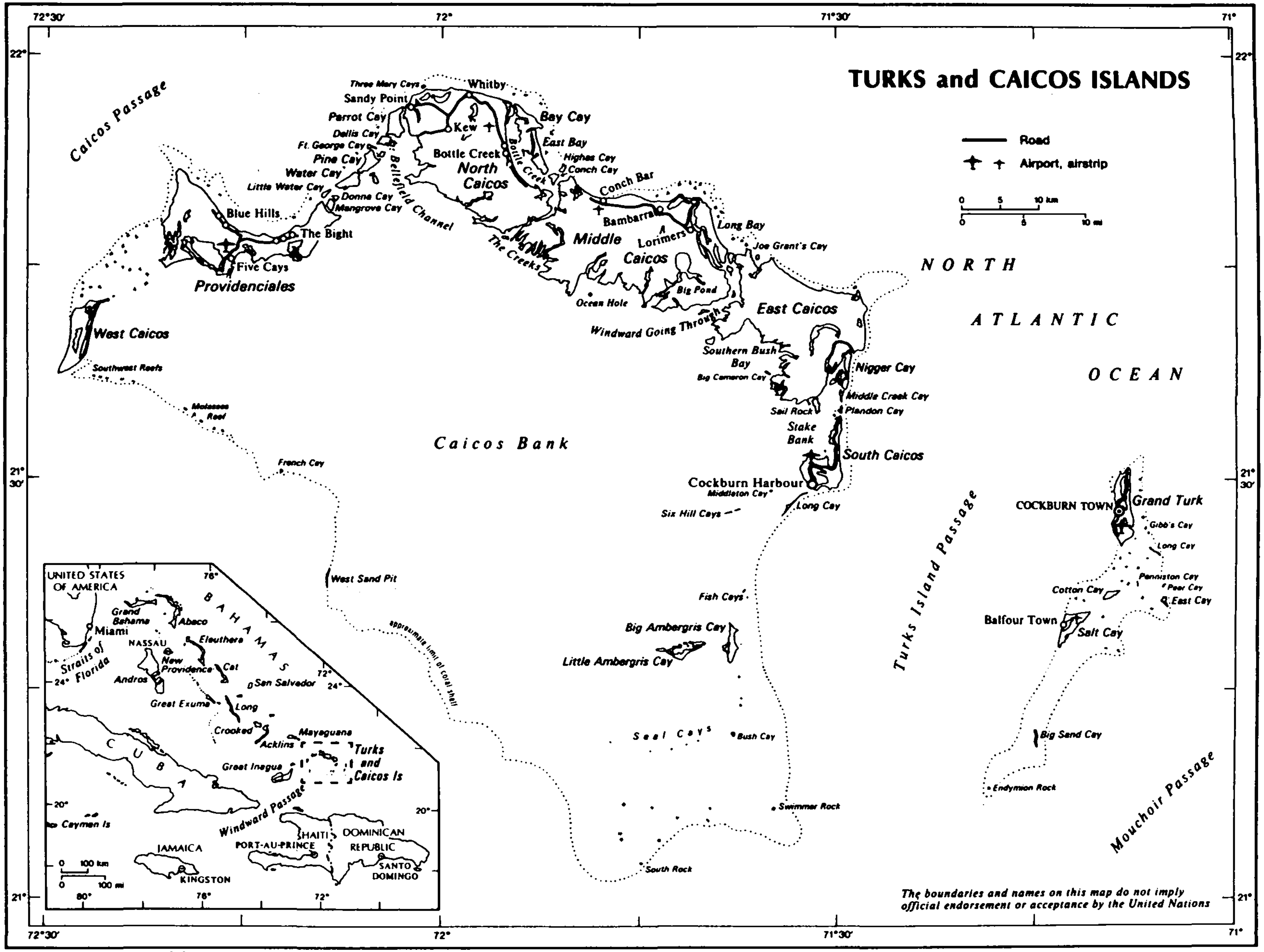


MAP NO.2976 Rev.1 UNITED NATIONS
APRIL 1985

Map 4. Turks and Caicos Islands

South Caicos has tried to diversify into lobster and conch fisheries, on the large Caicos Bank, but the early high prices have declined in competition from elsewhere. Grand Turk has the advantage of being the capital, but Government cannot afford for everyone to be a civil servant. Salt Cay has become depopulated with the movement of people to other islands. Local opportunities have not been great, and large numbers of people have emigrated to the United States and the Bahamas in search of work.

The second group, referred to here as the Lower Caicos Islands, has a different history. Although shallow pond conditions do exist in places, the somewhat higher convectional and frontal rainfall and surface flood run-off from the large areas of surrounding ground precluded the development of a salt production industry. Even there, however, fresh-water reserves are very small and a nascent sisal industry in the 19th century foundered upon the lack of sufficient good quality water for retting the fibre. The small village communities perforce fell back onto subsistence fishing and farming, although ground conditions are very harsh and require much toil to produce even simple crops. Emigration, therefore, either to the Salt Islands or the world beyond has long been a feature of life in those settlements.

In recent years, Government policy has been directed towards attracting investment to diversify the economy and improve the quantity and quality of employment opportunities at home. An expanding tourist industry, based on the presence of many good beaches and some of the best unpolluted diving areas in the world, is now becoming established on the island of Providenciales while the capital, Grand Turk, is attracting investment by off-shore financial interests.

## 1. Traditional water supplies

The traditional source of domestic water, as in other small islands of the region, is the house roof catchment and storage tank. That is, each resident makes his own provision for his basic needs. In times of drought he must obtain supplementary supplies from some centralized source such as a Government supply from public buildings or a purpose-made ground-level catchment; in the lower Caicos he may extend the life of his house reserves by using well water for washing and also used for drinking and culinary purposes during long droughts. The extent to which a house catchment supply can meet the needs of the occupants depends upon: the area of roof, volume of storage, number of occupants, condition of guttering and storage tank, use of water by individual occupants and actual rainfall. In general, an average family of five might reasonably look towards occupying a single-storey house having a total roof area of about 1,000 sq ft which, in a normal rainfall year, is sufficient to meet an average fresh-water demand of about 10 gal/head/day. It is important to emphasize that this does not include toilet flushing water which must be supplied from another source, possibly salt or brackish. Storage is needed to carry adequate reserves from the rainy season over the period of average drought, and statistics indicate that capacity ought to be about 10 gallons per sq ft of roof area.

It should be noted of course, that a considerable difference in yield results from different occupancy rates; a dwelling where childless occupants hardly had to worry about supplementary supplies may well come on the central ration list if replaced with a family of four or five; likewise, if a length of guttering is left unrepaired, a householder may well find himself short of water during the dry season and clearly some checks need to be made at intervals to ensure that any leaks in storage tank or plumbing fittings will be repaired. All these matters are obvious, but they deserve mention as they apparently often come as a surprise to householders.

Roof catchments as well as public ground level catchments and ground water supplies depend upon actual rainfall which comes from random events, however much we try to predict things by statistical evaluation. This is true anywhere but particularly so for small islands far to the south of the temperate westerly rain belt and north of the main inter-tropical convergence area. There are considerable variations in amount and seasonal pattern from year to year, so that a quoted average of just over 20 inches per annum must be recognized as a very generalized figure. The wet season is considered to be from September to December with subsidiary rains in April and May; January to March is statistically the dry period with March itself consistently having no measurable rain. Yet, at the time when many of these statistics were originally being abstrated, the wet season (September/December 1973) had only five days of significant rain, interpreted as not less than one-half inch over two days, and November, which is realiably the wet test month, recorded no such rain days. Similar stories could be repeated for different seasons in different years and this reflects the nature of the rainfall - a few heavy storms a year, of fortuitous occurrence.

It may be surprising that a roof catchment supply can work in such a climate but it does work reasonably well, for houses having a favourable catchment area/occupancy ratio and adequate storage. The recovery off a well-guttered corrugated galvanized iron roof is consistently 85 to 90 per cent of measured rainfall and sometimes over 100 per cent, which reflects the driving nature of the rain; even short, sharp storms of small total precipitation yield a relatively high run-off into storage under these conditions, and many modern roof coverings perform even better, yielding run-off even from dew. It is this immediate response to any precipitation, compared with a surface or ground water supply, which makes recovery from a disastrous drought so rapid.

The main deficiencies of such a system relate to the house roof area and the storage capacity provided. The first reflects the current standard of living of the occupants and, as it is to be expected that this will improve in time, the roof area per occupant should increase towards an acceptable figure. Storage capacity represents a large initial capital outlay; to avoid this, a great number of people rely on 50-gallon oil drums. This limits capacity, is unsanitary and, in any case, is becoming impracticable, as oil is now imported in bulk. Some assistance for providing storage for the poorer members of the community is clearly necessary.

New housing is required, by the Planning and Development Authority, to be provided with rain water storage capacity of 10 gal per sq ft of roof area.

## 2. Supplementary supplies

Notwithstanding the full development of private roof catchment potential, supplementary supplies will be required to cover basic deficiencies and demands during extensive drought.

Supplementary supplies are derived from:

(a) Public rain-water catchments;

(b) Fresh ground-water lenses where they exist;

(c) Brackish ground-water deposits, where they exist, desalinated by reverse osmosis;

(d) Salt water desalinated in distillation plants or by high pressure reverse osmosis;

(e) Barging of water from islands having spare capacity or from abroad.

Additionally, supplies of fresh, though not necessarily potable water must be made available for construction if the overall development programme in both public and private sectors is not to be adversely affected. Such water should also be available for small scale horticulture, garden and public area beautification and other similar uses. The definition of "fresh" for these purposes may be considerably more tolerant than for potable water and chloride contents of perhaps 1,500 ppm may well be acceptable.

The various alternatives considered practicable for the supply of supplementary fresh water are tabulated in table 60 together with the main advantages and disadvantages of each method.

It will be apparent that there is no single best solution; each of the various alternatives is limited in application or expensive in initial capital cost or running expenses or both. It is necessary to maintain existing private and public facilities in good repair, to ensure that new development accords with proper standards and that traditional and more recently introduced methods are welded into a properly managed system.

This may not be a popular view as it seems to run counter to the general technical optimism that some panacea was imminent which at one stroke would solve all the problems. To keep your pants up here you need belt, braces, suspenders and a spare hank of cord in your pocket.

## 3. Some basic data

Total local resident population about 8,000, probably 45 per cent of whom are located on Grand Turk. Overseas Turks and Caicos Islanders number some two to three times this number.

(a) Grand Turk: Private house storage tank capacity is about 2.75 million gallons, while public catchment storage capacity is about 4 million gallons. Rationing of public supplies commences when water in public tanks falls to 2 million gallons. Peak issues at height of drought average 100-120,000 gallons per week. Distillation capacity (from former United States Air Force Base plant) is about 12,000 gallons per day. Some private homes and hotels have installed small sea water RO units, total yield at present about 5,000 gallons per day.

Table 61. Turks and Caicos Islands: Sources of water supply, advantages and disadvantages

| Raw Water | Source | Advantages | Disadvantages |
|---|---|---|---|
| Fresh water | House catchment | Catchment available at house roof. Storage available at point of demand. Cheapest in long run - low running costs. | High initial cost of storage. Limited to roof area available. Shortage in drought. Water can be dirty. |
| | Public catchment | Public building roofs available for use. Storage in large amounts is cheaper to provide. often available near points of demand. | High initial cost. Separate catchments occupy useful land. Shortage in drought. Water can be dirty. |
| | Well fields | If correctly managed, supplies available in drought. Relatively cheap installation cost for supplementary water. | Great care needed in abstraction. Only available in restricted areas. Limited to amounts available. |
| | Barging | Water available from other countries. Can serve multiple demand points. | Expensive to operate for water alone. Requires storage both ends of service. |
| Brackish water | Reverse Osmosis | Cheapest immediate source of supplementary supplies if fresh water not available. Fast installation. | Only available in certain areas and resource very limited. Great care necessary in checking input water. Cost of pre-treatment and supervision can be high. |
| Salt water | Reverse Osmosis | Probably eventually cheapest capital installation. | Output water has relatively high salinity. Pre-treatment can be difficult. Energy costs high. |
| | Waste Heat Distillation | Energy and supervision available from power station. Cheapest non-fresh water source to run. Low salinity product. | Output limited by waste heat available. Expensive initial capital cost. Dependent upon proper power station facilities. |
| | Fuelled Distillation | No limit to output. Low salinity product. | Most expensive to operate. Troubles in maintenance. |
| | Solar Distillation | No conversion power needed, only pumping. Continuous output. Unsophisticated operational requirements. | Expensive in initial costs. Occupies relatively large area of land. Glass roofing subject to hurricane and other damage. |

(b) South Caicos: Total private house storage capacity is low and many people continuously depend upon issues from public tanks. There is a small brackish water RO unit producing about 1500 gallons per day. Water usually has to be barged in during severe drought.

(c) Salt Cay: Adequate private and public storage capacity due to depopulation.

(d) Other Caicos Islands: Generally inadequate house storage but supplementary supplies for washing, etc. are obtained from a few hand-dug wells as well as from a small number of public catchments.

(e) Providenciales: The great deal of new private housing is provided with adequate storage but supplementary supplies have, at present, to be obtained by tanker from a restricted ground-water resource. Both here and in the other lower Caicos Islands properly implemented development of the ground water resources is needed.

The large Club Med project just completed produces its own supply from a 50,000 gallon per day salt-water RO plant; the fresh-water yield to the sewerage system is treated and re-used for irrigation of the hotel area. There are a number of much smaller RO plants serving apartments, etc., which sell supplementary water as and when available.

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## II. EXPERIENCES WITH DESALINATION

### A. Bahrain: Training of staff for desalination plants

by Salman A.R. Khalaf*

#### 1. Historical background

The State of Bahrain relied for centuries on ground water and natural springs for all its fresh-water needs. The gradual, and recently the unprecedentedly high, growth in population and the birth of several light industries in the 1970s together have led to a very high growth in water demand (see table 61). These levels of water demand have contributed to the fast depletion of underground sources. More important was the simultaneous deterioration in ground-water quality. Records show that some well water salinity had exceeded the drinking water total dissolved solids (TDS) permissible limits specified by the World Health Organization. In most wells the water salt content reached 2,700 ppm to 3,000 ppm (TDS) and some areas have exceeded 5,000 ppm.

Table 61. Annual water production in Bahrain

| Year | Total production (million gallons) | Average/day (million gpd) | Annual increase in demand (million gal) | Percentage growth |
|---|---|---|---|---|
| 1973 | 5,467 | 14.98 | 378 | 7.4 |
| 1974 | 5,517 | 15.12 | 50 | 0.9 |
| 1975 | 5,804 | 15.90 | 287 | 4.9 |
| 1976 | 6,382 | 17.48 | 578 | 9.9 |
| 1977 | 7,469 | 20.46 | 1,087 | 17.0 |
| 1978 | 7,996 | 21.90 | 527 | 7.0 |
| 1979 | 8,897 | 24.38 | 901 | 11.3 |
| 1980 | 10,036 | 27.50 | 1,139 | 12.8 |
| 1981 | 11,730 | 32.14 | 1,694 | 16.8 |
| 1982 | 13,391 | 36.69 | 1,661 | 14.2 |
| 1983 | 13,726 | 37.61 | 335 | 2.5 |
| 1984 | 15,611 | 42.65 | 1,885 | 13.7 |

Studies (Water Supply Directorate, 1980) indicated that the high abstraction rate was the main reason for the rapid deterioration in ground-water quality. This was attributed to the steady drop in the piezometric pressure and the subsequent intrusion of sea water into these aquifers.

Several measures had to be simultaneously undertaken to control this situtation, the most important being:

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(a) Ground-water abstraction had to be legislated for and consumption curtailed;

(b) Non-conventional water resources were required to meet the needs of the country's infrastructure development.

The worldwide and regional experience was assessed and led to the selection of sea-water desalination by the Multi-Stage Flash distillation (MSF) process as being the most economic and appropriate method.

A long-term plan was formulated for the construction of desalination plants. The first phase was comprised of two 11,365 $m^3$/day plants (2.5 million imperial gallons per day), the first unit being commissioned in 1975 and both units entering commercial operation in July 1976.

Table 62 shows the current type, capacity and number of desalination plants, excluding those owned by the private sector.

Table 62. Desalination plants in Bahrain in 1985[a/]

| Plant type | Capacity $m^3$/d (million gpd) | No. | Year of commissioning |
|---|---|---|---|
| MSF | 11,365 (2.5) | 2 | 1975/76 |
| MSF | 22,730 (5.0) | 1 | 1984 |
| MSF | 22,730 (5.0) | 1 | End 1984 |
| Brackish water reverse osmosis | 45,460 (10.0) | 1 | End 1984 |
| MSF | 22,730 (5.0) | 2 | 1985[b/] |

a/ Excluding desalination plants for private sector.
b/ Expected commissioning by 1985.

In addition to the problems encountered in training and developing personnel for the running of the first two units, which have now completed almost a decade of operation, it can be seen from Table 62 that it will be necessary to take over a large number of new plants in a very short period. It must be appreciated that, however effective the training programmes are, it is unlikely that they will be able, in the time available, to prepare economically the required number of staff with appropriate skills and sufficient knowledge to run these plants in the most efficient and reliable manner.

## 2. Establishment and fulfilment of manpower requirements

The first desalination plants were introduced as part of a dual purpose plant comprising four steam-generating units whose bleed steam is used as heat input for the desalination process. Qualified personnel to run this complex were not available then. Desalination plant operators were not readily available in the international market at that time and, if available, they were scarce. Therefore, training of local Bahrainis in all related fields, and the water desalination field in particular, was emphasized.

One of the problems encountered after the take-over of the desalination plants was the manning requirement for safe and economic operation. The determination of the manpower needs, and subsequently allowing for proper training programmes to be established to fulfil these requirements, were not easily attainable due to the following constraints:

(a) The period of the early 1970s was marked with stress on meeting very high water and power demands;

(b) Lack of interest to work in unattractive working conditions;

(c) Low salaries compared to those offered by the competitive private sector;

(d) Alternative opportunities were open for young Bahrainis for academic training and higher education;

(e) The staff needed by the organization were from a very narrow band of the social structure, i.e., the requirements were for young Bahrainis with minimum high school, preferably a vocational type of education, and having a good command of the English language.

For a small country with a small population like Bahrain, establishing the optimum of personnel needed for running desalination plants was always an organizational objective. In the case of desalination, the country had to build up its own experience to determine not only the safe number, but also the most economic manpower levels needed. The tendency to over-estimate manpower requirements to be on the safe side, to prepare for an emergency and to ensure labour availability at all times without undue pressures was not only impossible, due to unavailability of experienced specialized staff, but also strictly curbed.

Table 63 shows the operation and maintenance personnel required for two units of 2.5 million gpd capacity each, MSF cross-tube type with pneumatic control. These manpower levels are considered from experience both the most practical and economical, and they have been used as a measure of comparison and as a target for future plants. These levels were also used as a basis for deciding the staff requirements for the new plants, currently under commissioning, with appropriate adjustment of the various categories to take care of the plants' specific design features, i.e., the degree of automation, type of process control, number of standby or common auxiliary equipment, etc.

Table 63. Summary of operations and maintenance staff for desalination plants in Bahrain

| Staff category | Existing desal plant (2 x 2.5 million gpd) | New desalination plant (3 x 5.0 million gpd) | New desalination plant (1 x 5.0 million gpd) |
|---|---|---|---|
| Technicians | 18 | 15 | 7 |
| Oper./Superv./ Skilled workers | 47 | 73 | 23 |
| Unskilled workers | 13 | 19 | 7 |
| Total | 78 | 107 | 37 |

Notes:

1. The above table excludes engineering supervision/mangement/ administration/planning and general services.

2. Personnel used per new distiller extension (35 persons for distillers 2, 3 and 4; and 37 persons for distiller 5) is less than that for distillers 1A and 1B (39 persons), because of more automation and advanced technology used in new plant.

3. For new plants, personnel figures are estimated requirements.

These manpower levels are affected by vacancies created by: (a) staff turnover: personnel leaving the organization; (b) promotion to other posts or departments within the organization; (c) re-organization: plant modification affecting operation and maintenance methods.

Therefore, irrespective of any apparent success of a manpower plan, a periodic review is necessary to confirm its continuing validity with the new organization objectives and policies.

## 3. Exploitation of sources of training

Unlike the power industry, personnel needed for operating and maintaining desalination plants are not readily available. For that reason, and for organizational efficiency, staff training and development had to be undertaken. This was also in adherence to the national objective of achieving self-reliance or "Bahrainization". Sea-water desalination was a relatively "new" technology to Bahrain, as well as to some neighbouring states. It was envisaged that all possible sources of training in this field must be utilized to achieve the organizational objective. Hence, all efforts were made to establish local expertise in this field for the management, as well as operation and maintenance, aspects.

The sources utilized to provide the theoretical knowledge, practical experience and competence for operating and maintaining desalination plants are summarized below. The varying degree of contributions of those sources of training to achieving the objective, and the problems and difficulties encountered in each area, are also discussed.

(a) Regional training facilities

In the absence of any form of training, particularly in the field of sea water desalination, regional assistance was sought from the State of Kuwait for training some Bahraini nationals. The reasons behind seeking Kuwait assistance, in the mid-1970s were:

(i) Distinctively close ties existed between Bahrain and Kuwait;

(ii) Kuwait had gained a wealth of experience in operating commercial size desalination plants since the 1950s;

(iii) Kuwait had well-established training facilities and all training courses were conducted by local instructors.

The willing and informal way this assistance was offered contributed to very successful results and helped achieve Bahrain's primary objective of giving local staff the basic theoretical knowledge and acquaintance with real working conditions and the industrial environment.

This form of training also helped in achieving one of the organizational objectives: to prepare the nucleus of local expertise in the field of desalination technology. The above reflects how user experience might be retrieved for the benefit of other users of this technology.

(b) Academic and theoretical training

As Bahrain emerged as a desalination plant owner in 1976, to overcome the lack of basic familiarity with this technology and its practical aspects, academic training for some Bahraini engieers was achieved by attaching them to a prominent educational institute. These engineers with higher degree qualifications in desalination technology have gained more in-depth information on the design and implementation of various desalination processes. This expertise was valuable and was used in assessing future project designs, evaluation of plant performance, testing of and modification of desalination plants, reviewing operating procedures and maintenance techniques.

In addition to the above, local engineers were encouraged to enroll in professional institutions and to participate in relevant international conferences that addressed desalination technology innovation, operational experience and allowed for exchange of views with other users.

(c) Capital desalination projects contracts

In the absence of a well-defined manpower plan, the lack of established training facilities, and the non-availability of experienced personnel for operating and maintaining future desalination plants, it was found absolutely necessary to utilize the desalination project contractor's personnel to cover for the unavailable qualified local staff required to run the newly built desalination plants.

More importantly, new plant specifications are drafted to take into account operation and maintenance difficulties encountered in previous plant designs (Khalaf, Al-Arrayedh and Al-Awadi, 1981). That is, previous experience gained locally or regionally forms the basis for improved design specification for the new plants. Furthermore, careful selection of consultants must be exercised. The role of consultants in recommending the selection of plant/equipment to be purchased is very crucial and must always be assessed.

(i) Provision of training

Training is specified in all capital project contracts to ensure the provision of reasonable training by the manufacturer. In recent contracts the cost of this portion constituted about 1-2 per cent of total costs of the contract, which covers training at the manufacturing works, and "on-the-job" training. The quality of training received from the contractor in recent projects was far below that anticipated, because training obligations in the contract were sub-contracted to another firm which had no experience in training operations and maintenance staff in desalination plant and no knowledge of the particular design being built.

Ideally, one would expect greater benefits to be gained from such training if it were conducted by use of "prototype" plants, thus helping the trainees to know physically the plants' expected operating characteristics and performance.

In most of these contracts, the contractor is expected to provide reasonable opportunities for the client's staff to familiarize themselves with the plant. From experience, again with the recent projects, very little has been gained due to the contractor's claim that such familiarization, particularly if it is "hands-on" type, will lead to delays in the plant erection and commissioning and consequently he must pay specified penalties.

(ii) Provision of staff back-up after plant handing over

This clause is added in the contract and normally represents about 2 per cent of the contract total cost. It is intended to ensure the continuity of the new plant's operation, at this period of high growth in demand, while local staff are being trained and gradually replacing the contractor's supplied personnel. Integration of local staff and the contractor's staff was not easily attainable due in most cases to the language barrier and unwillingness of the contractor to freely train the local personnel.

(iii) Plant design and material specification

Local experts are given the opportunity to participate in drafting or reviewing the technical specifications for new desalination plant projects. Knowledge of local circumstances and past experience in Bahrain or in the region is an essential factor in getting the most suitable plant.

The following are some of the essential specifications incorporated in the new plant contracts:

- Preference for automatic control as opposed to the manual/pneumatic control mode of operation will help resolve the pressing problem of shortage in number and quality of local staff.

- Plants must be designed with stand-by facilities for some major equipment, even though this will lead to higher initial capital investment, so that disturbance to desalinated water production will be minimized due to equipment breakdown.

- Only proven equipment and plant materials should be specified, to reduce maintenance costs and plant downtime.

## 4. "In-house" training - Part of the corporate strategy

Utilization of the available financial resources, particularly during the last decade, has been directed towards establishing the island's infrastructure and the diversification of sources of income via industrialization and establishing a regional banking centre in Bahrain. The rates at which various sectors of the economy have grown has allowed no time for preparation of well-defined long-term development plans. Human resources development specifically received very little attention during this period of economic and social change. As a consequence, as observed in most of the developing countries, Bahrain had the tendency to purchase the equipment, in this case desalination plant, and secure the operation and maintenance personnel at a later stage.

It was, therefore, noted that when setting priorities among organizational objectives, training and development of staff had not been a priority. Furthermore, in desalination project contracts, clauses pertaining to training were normally overlooked or given less weight when evaluating and selecting international contractors' bids.

In the early 1980s, achieving self-reliance had become a strategic objective. Efforts and plans were directed for the first time towards manpower planning and human resources development on a national level. Some of the issues tackled were:

(a) The vast change in educational systems to produce people of the right calibre for various sectors of the developing economy.

(b) An ambitious plan called "the 10,000 Trainee Scheme" was commissioned and was intended for training Bahraini nationals in the various skills needed in the industrial and banking sectors.

The former does not serve the immediate requirements of rapidly growing sectors of the economy by providing sufficient human resources with broad-based theoretical knowledge. On the other hand, the latter is still in its embryonic stage and, if successful, should provide people with reasonable practical vocational training. These resources will be suitable for development in specialized fields of the industry.

Considering the foregoing, the Ministry of Works, Power and Water, found it essential to improve on the casual form of training that existed in the 1970s, and to establish a well structured target-oriented form of training in place of the then predominant passive form of training, by observation or watching. Hence, a Training and Development Department was created to serve the power and water sectors' needs and fulfil the following main objectives:

(a) To implement the Government policy of placement of Bahraini nationals in all the organization positions.

(b) To provide training and education to build or improve individual's skills to perform their duties safely and efficiently in order to meet the required standard of performance.

## 5. Training programmes

For the potential power or water desalination plant operators or craftsmen, below is a brief description of the courses conducted for them once they successfully pass the screening test phase. Figure 44 is a schematic diagram of training programmes.

(a) Induction course (duration 6 months)

Provides the trainee with knowledge of the industrial environment, the organization, the role of employees/trainees and refresher courses in basic sciences, maths and English language.

(b) Basic course (duration 6 months)

After successfully completing the induction course, trainees will be taught applied science and technology and exposed to the foundation skills and elements of general education, including training in first aid, fire-fighting, safety, the use of workshop tools and machinery. After this course, successful trainees are screened and tested and, after taking into account individual interests, the trainees take specific courses in various disciplines such as:

- Operation of gas turbines or steam turbines or desalination plant;

- Maintenance of electrical or mechanical or instrumentation equipment.

(c) Specific course - desalination operation (duration 12 months)

Provides the trainee with skills to enable him to safely operate under supervision, desalination plants and their associated equipment. It will include regular actual plant visits and a period of on-the-job training under strict guidance and supervision to ensure that he gains practical knowledge and skills by participating actively and directly in useful work.

After the trainees complete these courses, they are attached to the appropriate stations for actual full time on-the-job training/work. The suitability of an individual for carrying out the duties is assessed by station management.

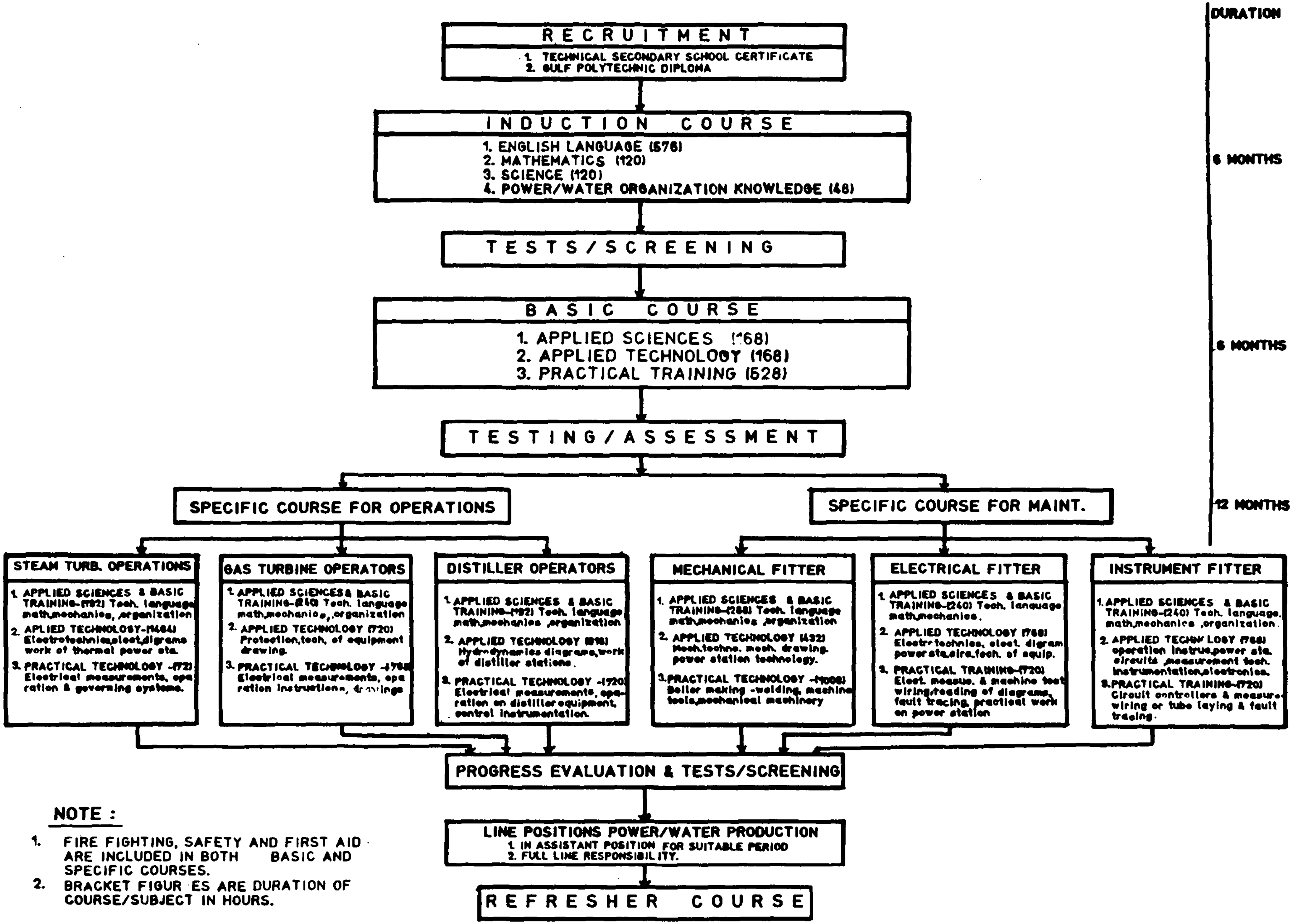


Figure 44. Schematic diagram of the Power and Desalination Training Programme in Bahrain

## 6. Training methodology

It must be stressed that modern training techniques once properly employed achieve the best results. In addition to using classroom laboratory and workshop, audio-visual aids are also used. All exercises simulate the actual conditions and requirements of the job as far as possible. In the case of operator training, sophisticated computerized simulators are employed during the course of the training programme. It was observed that the use of a simulator offers one of the best means of effective learning.

The concept of learning by observing others perform specific duties proved totally ineffective. On the contrary, target-oriented training has proved to be very successful. It must be stated that training merely provides the individual with the knowledge and skills to carry out particular activities. His performance depends not only on his ability but upon his willingness to apply that ability. It is in the management's interest to ensure that the morale and enthusiasm of all the staff, especially trainees who lack confidence, are maintained at a high level.

## 7. Problems in training

It is next to impossible to recruit professional instructors either locally or abroad. That is because the type of instructor required is not only a person who has the professional experience in the field of water desalination, which is rare to find, but also has the talents of teaching and passing knowledge to others easily.

In Bahrain, that problem was solved by actually developing one of our experienced desalination plant operators into an instructor. This solution to the problem of professional plant instructors in the field has proved very successful for two main reasons. The first is that this instructor has good practical experience and the second is that he speaks the same language as that of the operator trainees, hence overcoming the language barrier which hinders fast and better communication necessary for effective training.

During a period when private industry attracted some of the organization's experienced staff, mostly from the dual purpose steam power and water desalination plant, staff shortages were overcome by combining the steam turbine operation course with that of the desalination plant. This brought about flexibility of transfer of staff between the power and water production sides, and helped to offset the imbalance created by the loss of staff to private industry.

Because industrialization has come rather late to Bahrain, there is very little industrial experience and, because of this, it is found that operator trainees require a relatively long time to become acquainted with the work environment and to acquire the necessary discipline. For example, some trainees were not willing to work on a shift basis. Another problem encountered was with the stringent trainee selection procedures, which ensure that the financial investment in any trainee will not be lost due simply to the incompetence or failure of the individual. The candidates must have High School Certificates and have reasonable command of the English language. The latter means the organization is looking for people from a very narrow sector of the society.

## 8. Technology transfer

This issue is of importance to ensure sustained improvement in desalination technology. Technical co-operation between the developed countries (the manufacturers) and the developing countries (the technology appliers) is non-existent. Joint research and development programmes are negligible, due mainly to the absence of a technological infrastructure in the developing countries. The factors that limit the transfer of this technology are a combination of the following:

(a) The manufacturers are merely designers, the detailed process engineering, construction and commissioning are normally sub-contracted to other firms.

(b) The manufacturers act as equipment/plant suppliers, and for financial reasons, their organizations seldom employ operation and maintenance specialist teams permanently to provide necessary advice and support to the clients during the course of the desalination plant life. This is standard practice in the power industry.

(c) Labour laws and regulations in some manufacturers' countries prohibit the client's staff full-time training in their factories.

(d) The manufacturers are unwilling to disclose specific design features and other engineering information.

(e) Some clients are unable to provide their own staff to witness desalination plant erection and commissioning due to poor or non-existent manpower planning policies. It is often seen that desalination plants are built while the local manpower necessary to run them economically and efficiently is unavailable.

(f) The quality of most manuals, the tangible tool depicting technology transfer, supplied under desalination plant contracts, is in most cases sub-standard. The client's staff often have to review and re-format those manuals to suit the local training perception and their practical experience.

## 9. Users' expertise for reliable desalination plants

The Ministry of Works, Power and Water, has over the past ten years, gained valuable expertise and, despite the difficulties encountered, has managed to get its first two distillers run by Bahraini staff.

Several inherent design problems were solved by the engineering staff and the operating procedures were modified to ensure safe and reliable plant operation. Figures 45 and 46 show the trends in the plants' annual production levels and the staff productivity index respectively for the corresponding years.

Exchange of the users' experience in this field must be encouraged, particularly on a regional scale. Based on this joint research and development, programmes must be commissioned. Arab states in the region, through the Gulf Co-operation Council (GCC), must:

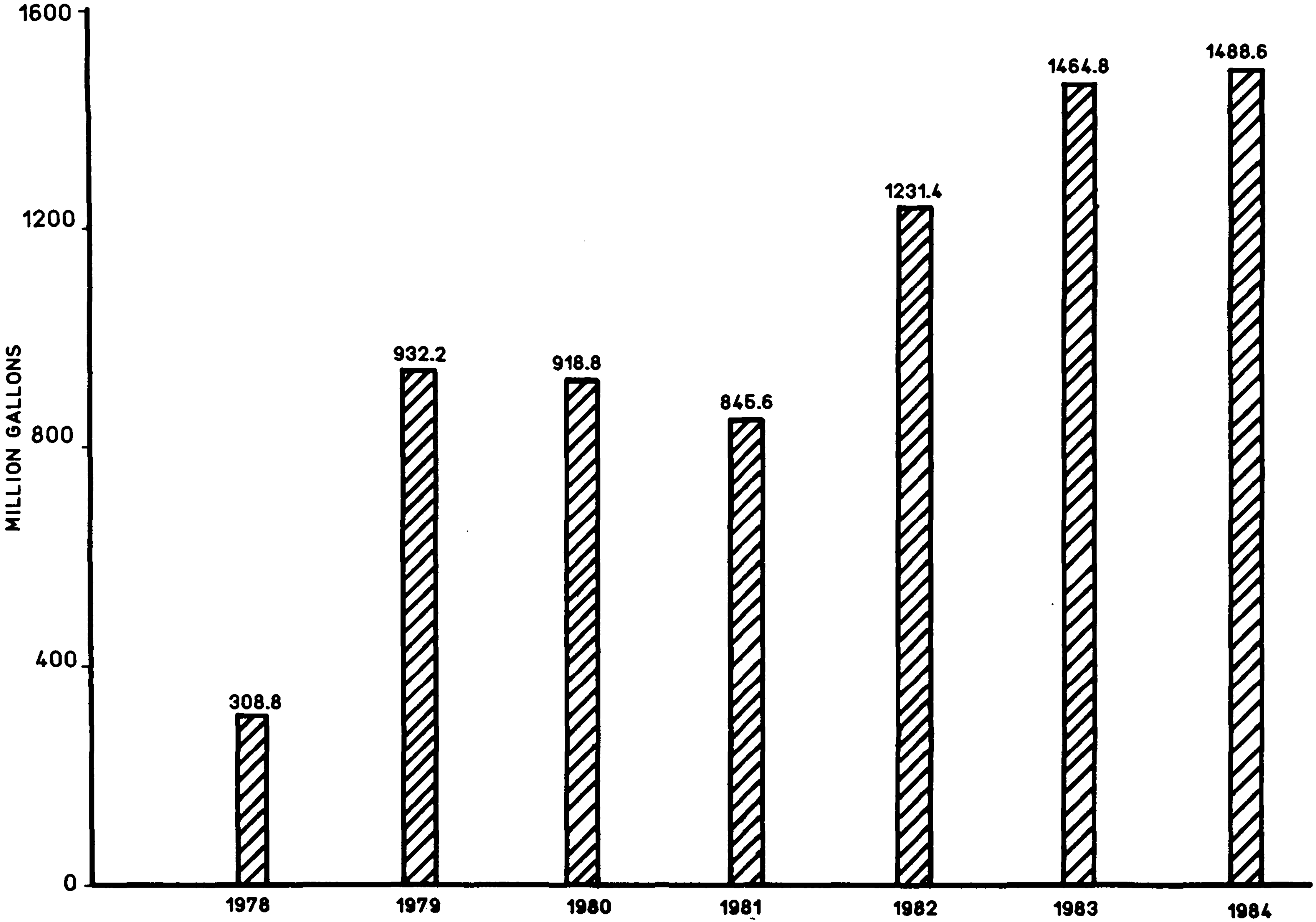


Figure 45. Water production per year for existing desalination plants in Bahrain

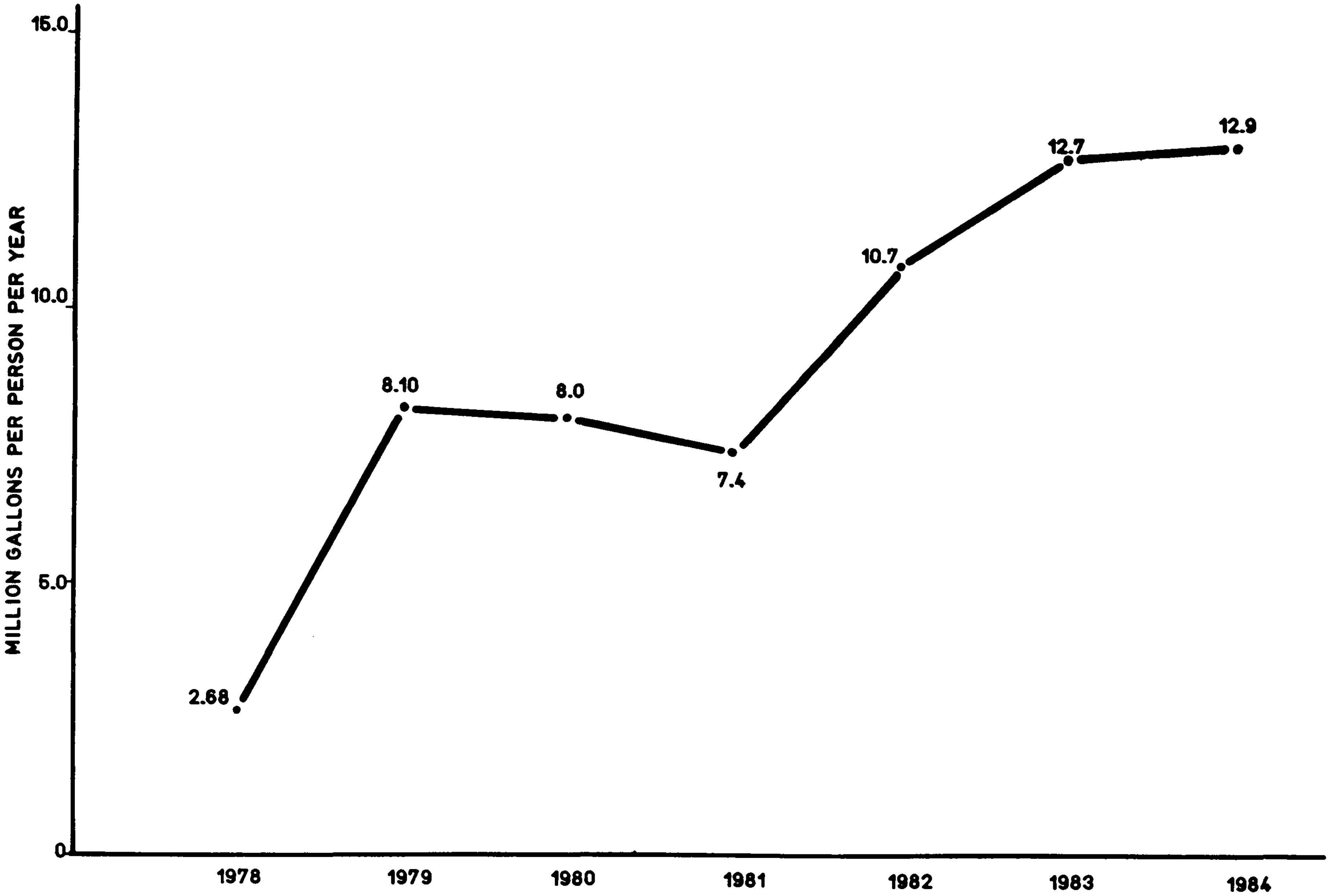


Figure 46. Water production to manpower ratio for existing desalination plants in Bahrain

- build up data banks on desalination plant spares, procedures and main equipment performance;

- standardize technical specifications;

- maintain a library of case histories and modifications to manufacturers' standard equipment.

Most important is the need to establish a centralized training activity for the GCC countries, utilizing the available training facilities and using the local experienced staff for conducting this specialized training.

## Conclusions

Long-term manpower planning is essential for implementing training and development programmes to fulfil self-reliance in any field.

Training methodology applying modern teaching techniques and the use of a simulator proved valuable in achieving the target-oriented type of training. Developing a local operator into an instructor proved essential for effective training.

All future desalination plant capital project contract specifications must incorporate clauses calling for elaborate training, conducted by the manufacturers. Users' co-operation is essential for building regional expertise and improvement in running plants reliability. Establishing regional technological infrastructure helps in improving transfer of technology from the developed countries.

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## B. Cape Verde Islands: Experiences with sea-water desalination

by Sonia Morais*

### 1. Introduction

Independent since 1975, the Republic of Cape Verde is situated in the North Atlantic Ocean between the Tropic of Cancer and the Equator, 455 kilometres off the western coast of Africa, at almost the same latitude as the Sahel (see map 5).

This volcanic archipelago has a very hilly relief and covers an area of 4,033 square kilometres and consists of ten large islands, nine of which are populated, and eight smaller uninhabited islands.

Santiago is the biggest and most populated island and its main town, Praia, is the political capital of the country. However, Mindelo in S. Vicente Island and Espargos in Sal Island are respectively the most important international seaport and international airport of Cape Verde.

Cape Verde has a sub-tropical dry climate with a short irregular rainy season; it suffers from constant drought cycles which have resulted in the desertification of the country.

The population of Cape Verde is composed of more than 300,000 inhabitants who are distributed among the islands. About 65 per cent of the people are employed in fishing and agriculture. The scarcity of rain considerably aggravates the rate of unemployment, which encourages people to emigrate.

The economy is based mainly on agriculture which is marginal, due to the unpredictability of the rains. In an effort to overcome this problem of economic instability, some industries were established and major emphasis was given to infrastructure related to the fishing industry and naval repairs, together with harbour development.

Most of these industries, namely the modern shipyard and the cold storage facilities are located in S. Vicente, as well as the international harbour, Porto Grande. The International Airport which is served every day by several international flights, is located on Sal Island.

Because these activities required considerable water for their development, and because of the very arid condition of the archipelago, sea-water desalination has been used on these two islands for more than 20 years. In S. Vicente the plants are run by a Government company currently called Electra, EP, which also manages the power station and distributes water and electricity to the city.

In Sal, the two major plants supplying the municipality are also run by Electra, while small units belong to the airport and to a hotel providing water for their own needs.

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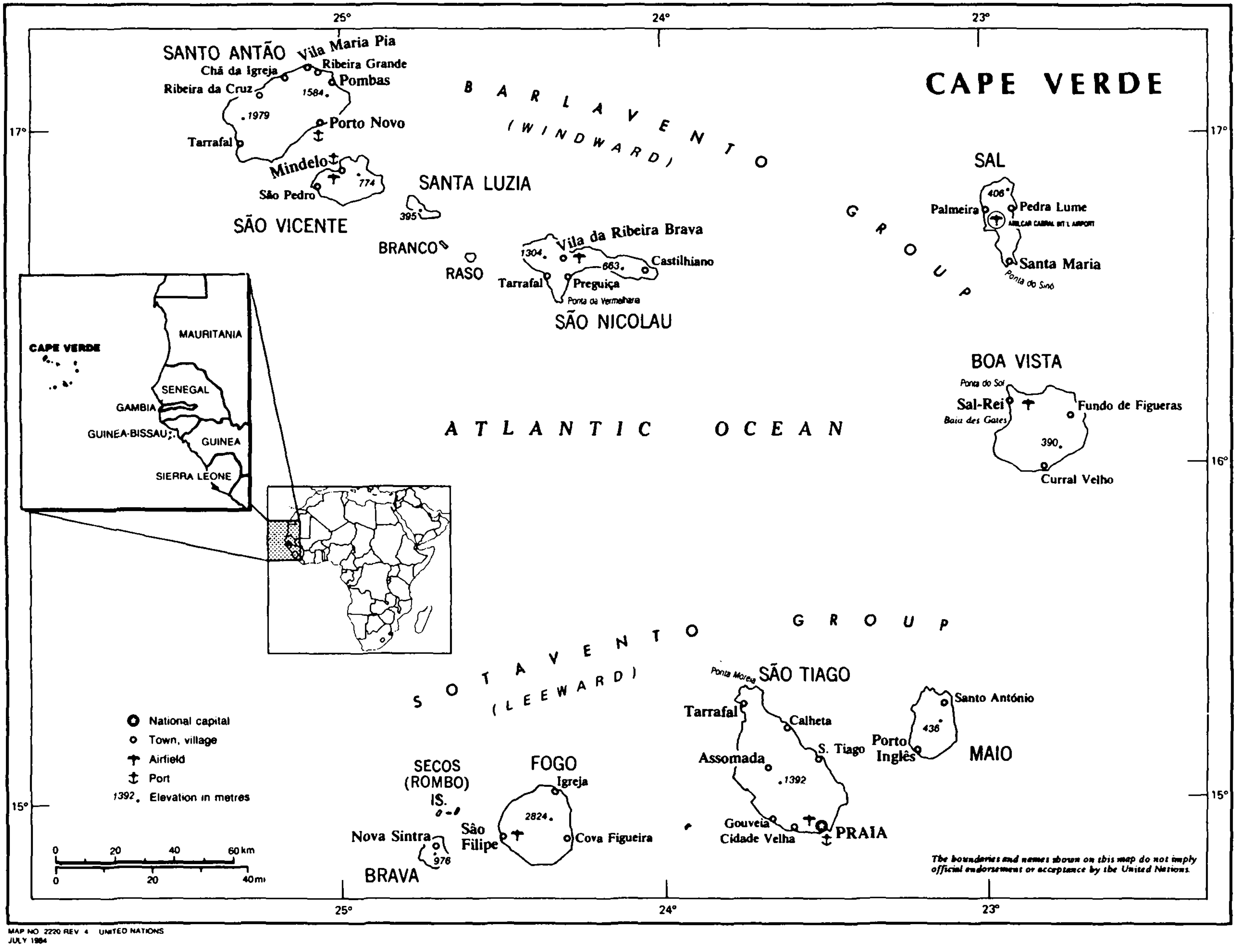


Map 5. The Republic of Cape Verde

Table 64 lists and gives information on the plants existing in the country.

Table 64. Sea-water desalting plants in Cape Verde

| Location | Capacity ($m^3$/day) | Contractor | Type | Completion Date | Observations |
|---|---|---|---|---|---|
| Sal/Airport | 21.6 | Ponzini | VC | 1959 | Out of service |
| S. Vicente | 2x1,100 | Babcock Wilcox | MSF | 1971 | " |
| Sal/Sta. Maria | 90.0 | Werkspoor Water | MSF | 1972 | " |
| Sal/Airport | 50.4 | Ponzini | VC | 1974 | Reserve capacity |
| Sal/H. Morabeza | 40.0 | Esmil | RO | 1978 | In service |
| S. Vicente | 2,400.0 | Esmil | MSF | 1981 | " |
| Sal/Airport | 34.4 | Chemilite | RO | 1982 | Reserve capacity |
| Sal/Palmeira | 3x220 | Polymetrics | RO | 1983 | In service |

Notes:
VC = vapour compression; MSF = multi-stage flash;
RO = Reverse osmosis

## 2. Desalting plants in S. Vicente

For many years, the drinking water supplied to the population of S. Vicente, and to the harbour, was brought from the neighbouring island of S. Antão, by tanker, while several wells provided the remaining water for other uses.

In the late 1960s with an increase of population and development on the island, the lack of water became a major constraint, and the first desalting plant was built in 1971.

### (a) Babcock plant

Designed by the Baldwin Lima Hamilton Co, and erected and commissioned by Spanish Babcock & Wilcox, the desalination plant, which is currently out of service, started to run in 1971. At start-up it could hardly reach the rated capacity of the design, and very soon many different problems were causing frequent voltage fluctuations.

The installation consisted of two production lines, each of which comprised a steam boiler, a turbo-generator and an evaporator train with a capacity of 1,100 $m^3$/day. The evaporator had a performance ratio of 8:1 and a top temperature of 120°C. The evaporator was a 43-stage, horizontal tube MSF type which used sulphuric acid as anti-scalant and had three heat rejector stages.

The high top temperature and acid treatment together with a very poor design with respect to the related auxiliary equipment (decarbonator, degasifier, vacuum system) made the control of scale and corrosion very difficult. This, combined with the lack of experience of the operators, resulted in problems from the very beginning of operation. A great number of leaks and holes were formed in the water boxes, evaporator shells and condensing tubes, while the brine heaters developed a considerable number of plugged tubes.

The scale that formed in the tubes was mostly hard calcium sulphate that completely clogged the tubes. During cleaning, which occurred almost every month, the clogged tubes often had to be unclogged using a drilling machine which caused the loss of several tubes each time.

Other critical problems were the following:

(i) The boilers had several plugged tubes; one of the boilers had to be completely retubed in 1977.

(ii) The turbines (there are a total of four, two coupled to the alternators and two coupled to the recycling pumps) suffered constant mechanical problems, which were responsible for a great number of the shutdowns of plant.

(iii) The sea-water pumps suffered considerable corrosion and wear.

(iv) The control instrumentation was practically inoperative most of the time, due to a lack of suitable maintenance by skilled personnel.

(v) In almost all of the pumps, valves and other equipment, considerable wear was caused by sand which was brought in by a badly designed sea-water intake.

The main merit of this plant was the existence of two production lines, which permitted a great flexibility in its operation, as it allowed the interchange of parts between lines and alternate maintenance, or shutdowns, of the equipment.

After 1977, a plant rehabilitation project was carried out. This consisted of retubing one boiler and replacing a turbo-generator, a recycling turbo-pump, a sea-water pump, several other pumps and valves, a complete set of air ejectors and instrumentation equipment. With this renewed equipment, a better control of the process chemistry, and some technical training programmes in the areas of pneumatic instrumentation and steam generators, the plant maintained operation for five additional years. During those five years, there was a considerable increase in production, which exceeded the production of the previous six years of operation.

However, the water costs were very high because of the intensive maintenance required and the low performance of the evaporators. At the end of 1981, a new plant began operation and the old plant was abandoned and considered as scrap.

(b) Esmil plant

Engineered by Esmil, in The Netherlands, the plant is currently in service and consists of a cross-tube, brine recirculating MSF evaporator with a capacity of 2,400 $m^3$/day when operating at a maximum brine temperature of 105°C. It used a polymeric anti-scaler and had a design performance ratio of 1:10. The evaporators and associated auxiliaries consisted of a sea-water intake, turbo-generator unit, piping systems, and electrical systems plus instrumentation and controls.

The amount of electrical power generated by the turbo-generator at full evaporator capacity is more than the plant's power consumption, so that the surplus power can be fed into a power station network. However, because the electrical system, at the time of the start-up of the plant could be considered rather unstable, with frequent voltage fluctuations, it was considered more convenient not to run the turbo-generator in parallel with the power station system, in order to avoid stoppages of the desalination plant.

For a period of time, the major reason for the stoppages of the evaporator was the high capacity of production, which exceeded the needs of the town. By decreasing the brine recirculating flow and top temperature at the heater outlet to the minimum permissible, it was possible to operate the plant below its 100 per cent design production (80-85 $m^3$/h), allowing longer running periods between stoppages.

To control scaling, more than 10 ppm of Belgard EVN was used after the start-up. This maintained the evaporator and heater tubes completely clean during almost two years of operation. It was then decided to slowly decrease the concentration of Belgard used in order to lower the operation costs and a dosing rate of 6 ppm was gradually reached, with the plant running for one more year without any acid cleaning. Acid cleaning is scheduled for the future and, after restoring the initial condition of the tubes, other additives will be tested.

Corrosion problems are found mainly in the sea-water pumps, whose materials have proved to be unsuitable, but in the evaporator chambers the corrosion is within the usual allowances, especially when compared with the old plant.

For several months the plant worked with only a few problems related to pump failures (intensive bearing wear), and other mechanical and electrical problems, which could be considered normal in this kind of facility. In general, the operation of plant was rather satisfactory, with the performance ratio figures being very close to the design.

However, during the last year and up to the present, the operation of the plant has been difficult due to several serious failures of the steam generator which was not supplied by the same contractor as the plant. This caused frequent stoppages and, above all, was responsible for a general shortage of water in the city, as the steam load requirements could not be satisfied and the brine top temperature was far below the one required to maintain a normal production capacity.

As a matter of fact, the production had decreased by about 25 per cent from the nominal capacity while the water demand was increasing progressively, making it difficult to find the opportunities to shut the plant down for maintenance.

The situation is very critical as the overhaul of the boiler, turbine, and even the evaporator itself is urgent but the shut down of the plant for several days is not possible, as the desalinator is the only souce of fresh water. This is a consequence of the existence of only one production line, which has proved to be a very erroneous concept for water-short areas. To overcome this problem, a new boiler is being procured and we hope that this problem will soon be corrected.

The last but not the least of the problems encountered is related to the sea-water intake whose design (made for the previous plant and only slightly modified for the new project) was very inefficient, resulting in the intake of large amounts of sand, stones and mollusc shells.

The molluscs grow inside the pipes between the sea-water pumps and the evaporator due to a lack of pre-chlorination. The formation of a conglomerate in the pipes causes a decrease in the internal diameter of the pipe in such a way that sometimes the feed-water pressure is insufficient for the circulation, at the same time that the shells cause the obstruction of the condensing tubes in the heat rejection section.

Another problem is that incoming sand causes considerable erosion on those parts through which the water circulates, such as the pumps. This lessens their efficiency and life. All of these problems cause frequent stoppages and decrease the output of the plant.

## 3. Desalting plants in Sal

With a small population, the life in Sal centres around the airport which, due to the nation's privileged situation and natural condition, is an important stop on the routes to the European, American and African continents.

The first desalination plant (and the oldest in the country) was built in 1959 by the airport and supplied fresh water for the village for many years. After that, two municipal plants and other smaller plants were built as the water requirements increased.

### (a) Airport plants

The first desalinator at the airport, made by Ponzini, was a 900 l/h vapor compression (VC) unit and its performance has produced satisfactory results, according to the owners. The main problems with the plant were related to the scale formation in the condensing tubes due to unsuitable scale control and cleaning. The operation was in the care of untrained personnel, which probably had a serious impact on its operation.

The materials were of first class quality, and in spite of the plant being out of service because of is small capacity, it is still in good condition.

The next plant was acquired by the airport in 1974 from the same supplier. It was also a VC and had a capacity of 2,100 l/h.

The operation has had, more or less, the same problems as the previous plant, i.e., high scale formation, followed by mechanical cleaning resulting in a high number of plugged tubes. It appears that the materials are not of such high quality as that of the old plant.

In 1982 a new plant was started, to supply a small group of houses built for the airport employees. It is a reverse osmosis (RO) unit made by Chemilite, with Chemi-RO SW/240-550 membranes (spiral wound modules). It consists of four units, each of them with four membranes producing a total capacity of 35 $m^3$/day. For the moment it is out of service, as the water produced at Electra is sufficient to cover the needs of the whole island.

As far as we know, the plant performed poorly during the short period of time that it was running, possibly because of lack of trained operators. The pre-treatment system includes chlorination; polyelectrolite and acid addition; and filtration by sand and cartridge filters before water is pressurized and directed into the membranes. Apparently, the plant is in operational condition and is maintained for reserve capacity.

(b) MSF plant in Santa Maria

Built by Werkspoor Water in 1972, the first municipal desalinator in Santa Maria consisted of a cross-tube MSF evaporator which used phosphate as an anti-scalant. The plant was designed with a nominal capacity of 90 $m^3$/day. The facility includes a steam generator, turbo-aerator, sea-water intake and pumps, auxiliaries and instruments.

Like the old plant in S. Vicente, the main problems encountered in the operation were related to the boiler, the turbo-generator and scale control. Mechanical cleaning of condenser tubes has been responsible for a large number of damaged tubes. Also, the sea-water intake and pumps caused several stoppages due to severe wave conditions and corrosion.

The performance of the plant became poor and, during its final years of operation, the cost of water was extremely high, due to the small production and the high cost of fuel on Sal Island. Also, the lack of trained personnel, at the time of start-up, could be responsible for a good number of the problems experienced during the operation of this plant.

(c) RO plant in Palmeira

This plant which is currently in service, is operated by Electra and is located in the village of Palmeira. It started operation in 1983 and is a dual purpose plant consisting of a power station and the RO installation. The RO plant consists of three units with a total of 33 modules capable of producing 660 $m^3$/day (3 x 220 $m^3$/day). The hollow fine fibre membranes are Du Pont B-10s, supplied by Polymetrics, Inc. The operation of the plant was characterized by poor performance, soon after start-up, as the product water capacity, quality and per cent recovery did not meet the design figure. After one year of operation, the production was reduced to 60 per cent of the design, and the salinity of the product was normally high, requiring frequent cleanings of the membranes.

Several reasons can be identified but the main cause for this is, beyond doubt, the inappropriate material furnished in certain parts of the equipment such as the pulsation dampeners at the suction and discharge of the high pressure feed pumps, which corroded heavily, causing fouling in the permeators due to carry over of corrosion products.

After 12 months of operation, inspection found a permeator completely and permanently damaged and covered by a thick layer of black ferric oxide. At least 26 membranes and several parts are to be replaced by the contractor but this has not yet occurred, creating difficulties in operation of the plant. Other important problems are related to the design of the sea-water intake and the use of flexible high-pressure hoses.

The sea-water intake is located in a natural well at the seaside, but under severe wave conditions, the bottom of the intake occasionally runs out of water, causing loss of pump suction due to entrapped air. During sea-water supply interruptions, both the desalination plant and the diesel generator (sea-water cooled) became inoperative.

Solutions to eliminate or reduce these failures are being discussed and alternatives being considered are: the construction of a new suction well; the installation of a submersible type suction-booster pump; the use of a self-priming pump; and others, which vary widely in cost and must be evaluated against their benefits. As concerns the flexible high-pressure hoses, all the original parts had frequent failures and leaked.

The pre-treatment of the sea water is as follows: the feed water is chlorinated from an electrolytic sodium hypochlorite generator, than a coagulant of the polyelectrolyte type is added. After flowing through the sand filters, a bisulphite solution is added to neutralize the chlorine and a hexametaphosphate solution is added to prevent scaling. After cartridge filtration, the water is pumped to the RO units at 800 psi. The product water is then treated with calcium hypochlorite. Other problems causing some interruptions in production are related to the non-delivery of chemicals and spare parts.

In general, this plant cannot be considered successful, as the production performance and water cost have not been what was expected. If the permeators and the defective parts are replaced and the sea-water intake modified, it is believed that the performance of the plant could be improved and the operation carried out in a more continuous and less costly manner than at present.

(d) RO plant of hotel Morabeza

Designed and built by Esmil in 1978, this plant was the first RO plant in the country and was considered to be a pilot plant for the contractor. It was installed to guarantee the supply of fresh water for the hotel serving mainly the aviation crew, since the poor performance of the municipal plant did not satisfy their needs. The plant, initially comprising a single permeator, was successively increased to two and three permeators to meet the increasing demands for the hotel. The permeators are of the B-10 type, made by DuPont and the total capacity is currently 40 $m^3$/day.

Initially, they have experienced a number of problems in the operation of the plant. The sea water was drawn from a well in the beach and after chlorination in a settling tank, it was filtered through a sand and a cartridge filter. A solution of sodium bisulphite was added to neutralize the chlorine. The feed water was very rich in suspended iron which caused serious problems of fouling in the permeators. They were cleaned every fortnight and their life was less than one year. Other problems encountered were the failure of the high pressure hose and the high pressure pumps. The flexible hoses were replaced by rigid pipes and the pumps were replaced by stronger ones.

Recently, a new intake with a modified design was made which eliminates most of the problems with the feed water. The intake consists of a set of tubes inserted 4 m deep in the sand, linked to a manifold. The tubes have a number of holes and are wrapped with a nylon covering. The sea water infiltrates through the sand and enters the tubes completely filtered and clear. From the manifold it is pumped directly to the sand filters at the plant. As the water is not exposed to light, there is no need to chlorinate the feed water nor to add bisulphite solution. Besides, at this point of the beach, the water is clean from suspended iron. After cartridge filtration, the feed water is pumped to the permeators at 60 $kg/cm^2$, without any other chemical treatment.

At present, the permeators operate for six to eight weeks between cleanings and those that are in service are about 18 months old. After this new intake system was installed, most of the operating problems have been eliminated and the operation costs were lowered considerably, as no chemicals were used and membrane life was increased.

In case of higher demand, the production can be slightly increased by raising the pressure of the pumps to 70 $kg/cm^2$. The quality of water is good. In general, this plant can be considered to be performing successfully and the maintenance is excellent.

## 4. Comparison of processes

From the description of the plants and their operation, one can conclude that all the processes have their specific problems and it is difficult to decide which is the more convenient.

Considering the complexity of the operation of an MSF plant, with its steam generator, turbines and electrical systems requiring trained personnel, the rather long elapsed time between the starting and production, and especially the higher specific energy consumption, reverse osmosis would appear to be a much more attractive process for desalination.

However, some of the disadvantages of reverse osmosis are the requirement for substantial feed water pre-treatment, uncertainties in the membrane life and replacement cycles, and poor quality of water.

The cost of water is one of the most important factors in evaluating a desalination process. Based on the working results for the two more representative plants currently in service, a cost analysis including the more significant costs of production was performed and results are given in table 65.

It is quite clear that the cost of the Sal water produced by reverse osmosis is considerably higher (while its quality is lower), in spite of the lower energy cost. One of the main reasons is the high capital cost.

However, for small capacities (below 1,000 $m^3$/day), our experience shows that the cost of the water produced by distillation would be even higher. As a matter of fact, the cost of the Sal water immediately before the starting of the RO plant was as high as US$20.00/$m^3$.

Table 65. Costs of water in Cape Verde, 1984 (US$/$m^3$)

| Type of cost | Mindelo MSF (2,400 $m^3$/day) | Palmeira RO (3 x 220 $m^3$/day) |
|---|---|---|
| Capital | 0.243 | 1.346 |
| Fuel | 1.433 | - |
| Electricity | - | 0.809 |
| Chemical | 0.040 | 0.331 |
| Labour | 0.195 | 0.744 |
| Membranes | - | - |
| Spare parts | 0.030 | 0.099 |
| Total | 1.941 | 3.329 |

Notes:

1. These costs are considered at the outlet of the facilities and do not include the distribution costs or losses.
2. The membrane replacement was not considered as it did not represent a cost at the time of this study.

Another important factor which can be responsible for a great number of problems and the shortening of the equipment's life is the lack of skilled personnel. Our company is giving major attention to this problem, and a number of people have been trained in the fields of steam generation, pneumatic and electronic instrumentation, diesel mechanics and, of course, theory and practice of desalination and operation and maintenance of plants. However, the majority of persons doing shift work and responsible for the running of the plants belong to the roll of workers, and their training is being done on-the-job mostly at the cost of expensive mistakes. In general, the operation of the RO plant is much easier, as long as correct chemical control is carried out.

Regarding maintenance problems, they are comparable between the two processes. The difficulty to obtain spare parts promptly is due to the long distance from the supplies and constraints of stocking a large amount of parts and chemicals. The possibility of a stoppage due to lack of materials must always be considered. Another important question which affects the operation of the plant and cost of water is the fact that, as a developing country, most industrialization projects require external financing. That financing imposes certain conditions on the budget and suppliers that do not allow a choice of technology, according to our experience. Therefore, it is quite common that the cost of the plant is cut down and after the commissioning the spare parts are then sold to us at exorbitant prices, as well as the technical assistance which, in most cases, is very neglected.

## 5. Conclusion

Sea-water desalination is proving to be more and more a technology that is playing a most important role in the development of Cape Verde's water resources. Its utilization on a large scale is already a fact and shortly desalination will be extended to most of the islands.

Space limitations do not allow for a more exhaustive discussion on the desalination plants than what has been described in this paper. Only the main features and most important events in their operation were emphasized. From this description one can get the feeling that in general, the desalination operation in Cape Verde cannot be considered a complete success, as the performance and life of plants are less than designed and the costs of the water relatively high.

However, this matter should not be judged on these bases alone. The fact that desalination is a new technology, the lack of trained personnel in a country with few industrial traditions, the long distance from the plant to the delivery centres for spare parts and chemicals, the lack of preventive maintenance due to the imperative need to make water continuously, some unfortunate design decisions, all have made plant operation a very difficult task. From the mistakes made and bad breaks encountered, enough has been learned to make new ventures more successful and this is the main contribution of these years of experience with sea-water desalination technology.

## C. Curaçao: Drinking water supply

by H.T.M. Gouverneur*

### 1. Brief history

Up until 1928 only well and rain water were used as drinking water on the island of Curaçao. To meet the increasing demand it became necessary to install in 1928 the first unit for converting sea water into drinking (potable) water, by means of a submerged tube distillation process.

In that process, water is brought to the boiling point by the addition of heat in tubes that are submerged in a pool of water. The capacity of the first plant was approximately 60 $m^3$/day.

One of the problems with that system is that the tubes were subjected to heavy scale formation on the outside of the tubes (calcium carbonate, calcium sulphate) and had to be manually cleaned every three weeks.

Later it was shown that by dosing ferric chloride into the sea water, the running time could be extended substantially. In 1959, it became possible to couple the water production with electricity production by using steam from the turbines to supply heat to the submerged tubes. This combination with electricity generation resulted in reduced production costs.

In 1963 the first two multistage flash (MSF) evaporators were installed with a capacity of 6,000 $m^3$/day each. The principle of that system is that spontaneous boiling (flashing) can be promoted by introducing water in a chamber through an orifice, which causes the water pressure to drop below the saturation pressure at that temperature.

With MSF evaporators the boiling occurs in a series of stages coupled through orifices to each other. The evaporators, which were installed in 1963, were dosed with polyphosphates to control scale formation. At present the total capacity of water production at the Mundo Nobo plant of the Water and Power Company for Curaçao (Kompania di Awa i Elektrisidat di Korsou, N.V. or KAE) is 37,000 $m^3$ per day. As a result of age of some of the production units, the reliable capacity is only 27,000 $m^3$ per day.

The daily average water usage of the island is approximately 27,000 $m^3$ per day, so theoretically the demand can easily be met. But still, because of the relatively small water storage capacity of the island (approximately 120,000 $m^3$, which at the current water consumption rate means not even five days' supply) and the unreliability of some of the production units, water supply has been through critical periods repeatedly in the recent past.

This situation will continue until the water storage capacity has been extended, and new more reliable production units have been installed. A summary of this historical review of distillation plants in Curaçao is shown in table 66.

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Table 66. Historical Review of distillation plants in Curaçao

| Year of installation | Manufacturer | Type | Capacity ($m^3/d$) |
|---|---|---|---|
| 1928 | Prache & Bouillon | Submerged tube | 60 |
| 1929 | Weir | " " | 240 |
| 1930/32 | Weir | " " | 240 x 2 |
| 1938/43 | Weir | " " | 240 x 2 |
| 1948 | Weir | " " | 240 x 6 |
| 1959 | Weir | " " | 2,000 x 2 |
| 1963 | Richarson Westgarth | MSF | 6,000 x 2 |
| 1970/71 | De Schelde/Wier Westgarth | " | 4,000 x 2 |
| 1977/78 | Stork/Werkspoor | " | 8,500 x 2 |
| 1984 | Esmil | " | 10,000 |

## 2. Present situation and production techniques

As mentioned, the total water production capacity at KAE is 37,000 $m^3$ per day divided among six production units (multi-stage flash evaporators) as follows:

| Evaporator | Capacity ($m^3/d$) | Year of installation |
|---|---|---|
| V1 | 8,500 | 1977 |
| V2 | 8,500 | 1978 |
| V3 | 10,000 | 1984 |
| V9 | 4,800 | 1963 |
| V10 | 2,800 | 1963 |
| V12 | 2,400 | 1971 |

Evaporator V3 has just now finished its one year guarantee run and is in operation without major drawbacks.

Evaporators V1, V2, V3 and V12 use high-temperature additives combined with sulphuric acid as anti-scalant, while evaporators V9 and V10 are using hexametaphosphate.

Since 1963 all the installed evaporators were of the MSF type. So we can say that we have over 20 years of experience with that type of water production. Figure 47 illustrates how the MSF plants are connected to the electricity generation facilities so that desalting plants can utilize the low pressure steam from the steam turbines. This dual purpose mode of operation has reduced energy costs.

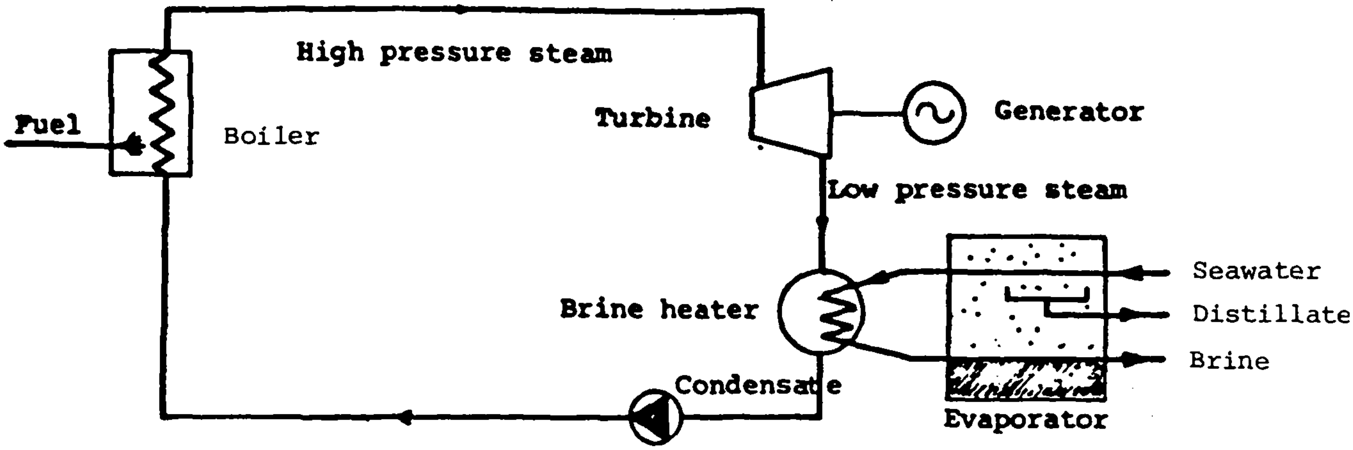


Figure 47. Production technique of a multi-stage flash (MSF) evaporator connected to a power generation facility

The heat released from burning fuel is used to produce high pressure steam in several boilers. This steam is initially conducted through steam turbines, generating electricity and then conveyed (as low pressure steam) to the brine heaters of the evaporators, where sea water is heated to the boiling point. The heated sea water then evaporates in the flash chambers of the evaporator. A portion of this vapour is condensed and collected as distillate which is used for potable water.

The low pressure steam which has transferred all its heat to the sea water in the brine heater, has condensed and is returned to the boilers to be heated up again. The distillate produced in the evaporators is passed through akdolite filters for hardening and pH increase.

Further it is passed through coal filters for removal of any organic matter which might be present. After this, the water is of potable quality and is stored in the storage tanks at KAE. From these tanks the water is pumped to the water distribution company storage tanks scattered all over the island.

In the delivery contract with the water distribution company, standards have been set for water quality, both chemical and bacteriological. These standards have to be met at all times and great care is taken in monitoring the water quality. Water samples taken several times a day are analysed at the KAE lab, while as a double check bacteriological analysis is also carried out by the "Landslaboratorium".

We can say that without doubt Curaçao's drinking water is one of the world's best.

### 3. Difficulties and problems

The problems associated with water supply in Curaçao are the following:

(a) High fuel costs are one of the main causes of the island's high water and electricity prices.

(b) One of the biggest problems is the maintenance of the evaporators in order to be able to meet the present water demand and required quality. This is both a financial and a technical problem.

(c) In order to keep ahead of the increasing demand and to be able to maintain the water production costs within reasonable limits, high investments have to be made for larger and more efficient production units.

(d) The unaccounted-for water is estimated at an incredible 30 per cent.

(e) The water distribution network is not well balanced. Some areas might experience a shortage of water while at the same time other areas have a surplus.

(f) The water storage capacity has to be increased to at least 250,000 $m^3$.

(g) Favourable financing arrangements for new projects are difficult to obtain. Because of this, old and inefficient units have to be maintained in operation for prolonged periods, resulting in higher production costs and consequent financial losses which are not beneficial to KAE's liquidity position.

### 4. Financing and price policy

Considerable sums have been invested lately in the KAE to secure the electricity and water production in the near future. Substantial amounts will still have to be invested to maintain an adequate supply of fresh water for the island. The finance required for these investments consists mainly of short-term suppliers' credit and commercial loans (See below).

The problem with this type of financing is that the redemption does not at all coincide with the depreciated amounts. While depreciation periods of the equipment vary between 15 and 25 years, the repayment time of the largest short-term loans varies between 5 and 8 1/2 years.

If these short-term credits could be substituted by a longer-term credit with a more moderate interest rate this would alleviate the liquidity position of the company considerably, resulting in a stabilization or maybe even a lowering of water (and electricity) tariffs.

Summary of financing received (historical figures)

| | Amount (Afl. 1,000)[a/] | Interest (per cent) | Redemption (Years) |
|---|---|---|---|
| Suppliers/Buyers | approx. 77,700 | 8.5-12 | 5-8.5 |
| Commercial loans | approx. 23,000 | 11-17.5 | 3-15 |
| Netherlands Development Funds | approx. 42,600 | 2.5 | 25 |
| Island territory | approx. 2,000 | 8 | 20 |

a/$US 1.00 = Afl 1.80 (1985 period average)

## 5. Strategies to overcome financial problems

The following are suggestions to improve the financial problems:

(a) Investing in more efficient and reliable units to reduce production costs.

(b) Operating the existing units as efficiently as possible.

(c) Reorganizing the water distribution company's system of collecting fees in order to reduce outstanding accounts receivable.

(d) Reducing unaccounted-for water.

## 6. Offers and requirements in terms of horizontal co-operation

The Water and Power Corporation of Curaçao can offer the following:

(a) Experience in combined sea-water distillation and power generation (dual purpose) plant.

(b) Experience in control and monitoring of water quality.

(c) Experience in setting technical and design standards for evaporators.

The KAE continues to have the following requirements:

(a) Methods relating to losses and control of unaccounted-for water.

(b) Experience in negotiating favourable financing arrangements with international agencies.

(c) Mathematical models for water resources optimization (balancing of distribution network).

(d) Experience in sea-water desalination with Reverse Osmosis.

## D. India: Overview of water desalination research for supplying water to some areas affected by salinity

by B.P.C. Sinha*

### Introduction

Every citizen of India is to be provided with a safe drinking water supply by the end of the International Drinking Water Supply and Sanitation Decade, in 1990. The Prime Minister's new 20-Point Programme also includes the ambitious task of providing all the identified problem vilages with a potable water supply.

The Master Plan for the Decade estimated that the rural population amounted to over 520 million in 1981, against the country's total population of over 670 million. The total rural population expected to be covered by the end of 1985 was almost 300 million. It has also been estimated that the population in rural areas in 1991 would be over 600 million. Interpolating these figures, the target population to be covered by 1990 would be 585 million. If the sixth plan target of covering almost 300 million by late 1985 is achieved, the balance of population to be covered during the Seventh Plan would be 285 million.

In order to identify the villages which need immediate attention, a country-wide survey was conducted. The criteria for identification of problem villages prescribed by the Government of India were any of the following:

(i) Villages where no water source existed within a distance of 1.6 km or where ground water was available at a depth of more than 15 metres, or in hilly areas, villages where water sources were available at an elevation difference of more than 100 m from the habitations.

(ii) Villages where the water sources had excessive levels of salinity, iron, fluorides and or other toxic elements hazardous to health.

(iii) Villages which were exposed to the risk of water-borne diseases, such as cholera, guinea worm etc., due to pollution of the available water.

The total number of villages identified under each of the above categories were 157,895, 46,662 and 26,227 respectively.

Map 6 shows the general distribution of ground water in the country. In a large part of the villages under category (ii), the problem of saline and brackish ground water exists. Finding alternative sources is not feasible. Such areas will have to receive last priority because the schemes to serve these areas would involve high costs. However, the needs of the people inhabiting those areas cannot be ignored. One of the only available choices is to adopt desalination in such situations.

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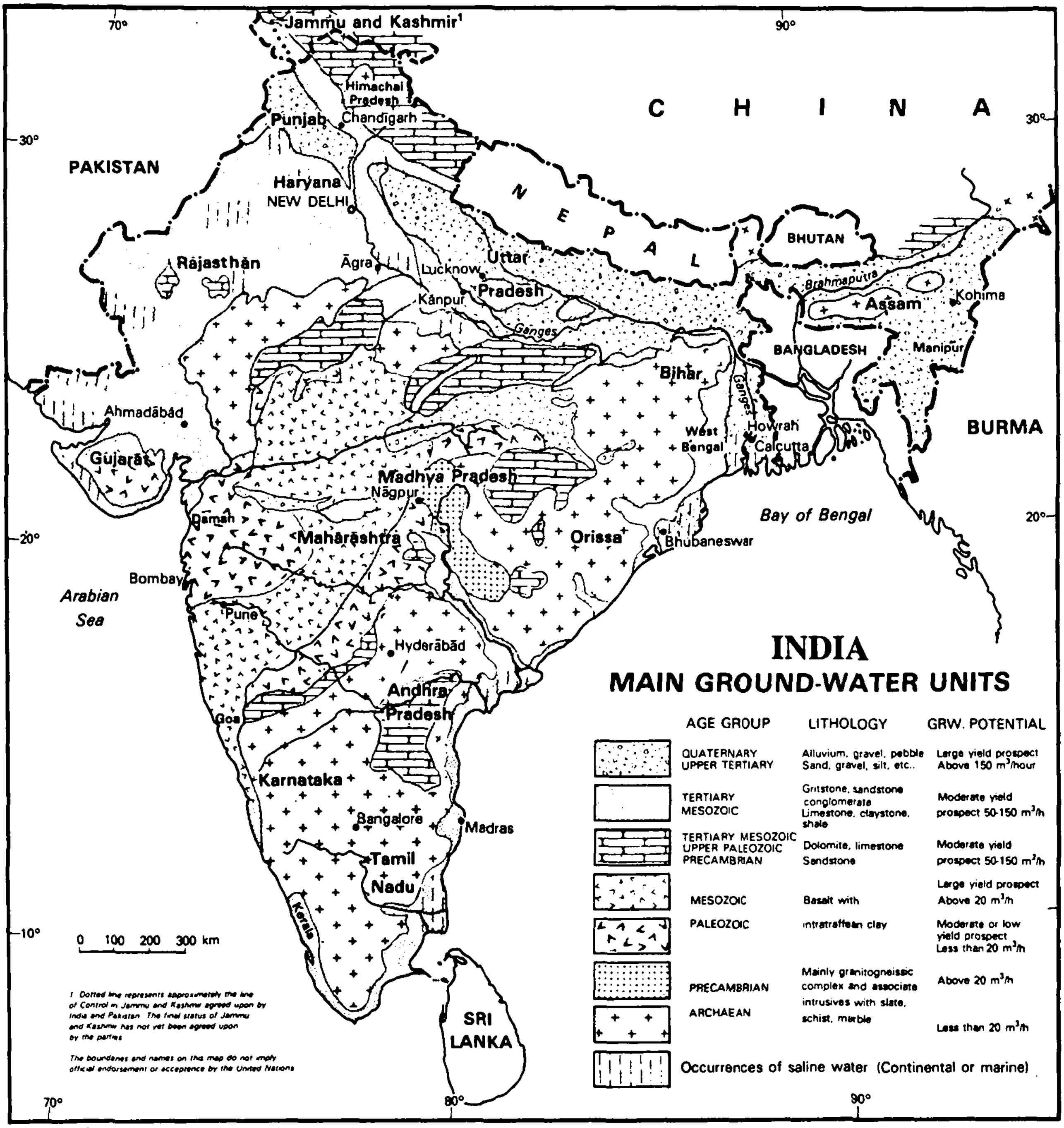


MAP NO.3323.17 UNITED NATIONS
MAY 1985

Map 6. India: The distribution of ground water

Although extensive research has been carried out by the various research institutions in the country and demonstration units have been set up, there is still an urgent need for technology transfer to permit large-scale practical application in the field. The critical factors needing classification are:

(i) The scope for this technology and user response.

(ii) Cost profile and efficiency of existing systems including operation and maintenance.

## 1. Desalination process

The various desalination processes that have so far been tried in India are:

(a) Processes involving thermal energy

Submerged-Tube Distillation
Multi-stage Flash Distillation
Vertical-Tube Evaporation (VTE)
Horizontal-Tube Multi-effect Process
Solar Distillation

(b) Processes requiring mechanical/electrical power as the main input

Vapour Compression Distillation
Freezing
Reverse Osmosis
Electrodialysis

(c) Other processes

Ion Exchange
Solvent Extraction
Hydrate Process

The above processes have been employed with varying success in the desalination of sea water and brackish water. However, each process has its limitations and is suited for specific situations.

Submerged tubes were used in the old designs of multi-effect desalination plants, but currently are not in use. The process became obsolete with the development of the multi-stage flash distillation process which is at present one of the most widely accepted process for sea-water desalination. VTE and horizontal-tube multi-effect processes are not in much use now except in ship-borne evaporators. Solar distillation is good for very small applications.

The combined VTE-MSF process is next to the MSF distillation process for large-scale sea-water desalination. Although the process is more complex in design and operation, it appears to have definite cost advantages. Vapour compression distillation is widely used in ship-borne evaporators but it is not of significance for large-scale evaporation, especially because the operation of vapour compressors is beset with difficulties due to entrained brine in the vapour stream. Due to high refrigeration costs in India, the freezing process is too expensive and will not be competitive. Reverse osmosis (RO) and electrodialysis (ED) are accepted processes for brackish water desalination on a large or small scale. Solvent extraction and hydrate processes are out of consideration these days.

From the various desalination techniques available, it has been considered that RO, ED, and solar distillation were the three techniques appropriate to the desalination of brackish water, particularly in the rural areas. Some important reasons for this are that the water requirements in rural water supply schemes are small and that such schemes would be dependent on ground-water sources where the quality would not be variable. Additionally where brackishness was associated with fluoride and nitrate problems, water desalination offered the potential to eliminate such hazards.

## 2. Water desalination research in India

Water desalination research is principally carried out by the following national organizations: the Central Salt and Marine Chemicals Research Institute (CSMCRI); the Bhabha Atomic Research Centre (BARC); and the Defence Laboratory.

Salient features of the work done in application of the various desalination techniques are as follows:

Solar Stills. The CSMCRI has constructed two stills of 20 $m^2$ each on the roof of a garage to supply distilled water. The design adapted aluminium sections and eliminated use of pre-cast items.

Under the "science for villages" programme, two plants were set up in Gujarat, one in Rajasthan and one in Laksha-deep. The capacities of these plants ranged from 2,000 to 8,000 litres per day. In these applications, the desalination costs varied from 34 to 19 Rupees[1/] per cubic metre for plants from 1,000 to 10,000 litres per day.

Thermal Processes. A 3-stage flash distillation facility was set up at Bhabha Atomic Research Centre and operated for 2,400 hours. At present a 425 $m^3$/day 33-stage MSF plant is under construction.

A five-effect VTE plant was operated for about four years and a 250 $m^3$/day VTE-MSF plant has been designed by BARC and work on setting it up is in progress. Regarding ship-borne plants, BARC has designed, fabricated and operated a small pilot plant, while a larger unit is currently being fabricated.

Reverse Osmosis (RO). Research and development work on RO was started in the CSMCRI during 1968-69 with a view to developing plants using brackish water desalination using appropriate technology. Design and fabrication of tubular plants incorporating indigenously developed cellulose acetate membranes was standardized. Those plants had capacities ranging from 10 to 20 $m^3$/day. One plant was set up in a village in Amreli district, Gujarat, and operated for over four months to supply good quality drinking water to the village. A few plants were fabricated and supplied to government and semi-government agencies.

1/ $US 1.00 = Rs 12.37 (1985 period average).

The Institute has recently set up an RO plant of 10 $m^3$/day capacity, based on using spiral configuration membranes for the Gujarat Agriculture University near Ahmedabad. This plant treats well water of 5,000 ppm to produce potable quality water to supply the research staff stationed at Arnej. The plant was in continuous operation for two years maintaining a steady and satisfactory performance. Another plant of similar capacity was fabricated for Central Marine Fisheries Research Institute, Mandapam.

A mobile unit comprising an RO plant of 10 $m^3$/day with all other accessories such as the filtration unit, etc. housed in a passenger bus, was designed for demonstration of desalination technology in villages where the available water is brackish. This creates a visible impact on the people and an awareness in the villages about the application of desalination technology for rural water supply programmes.

The BARC has done a considerable amount of work on the RO processes. A module based on tubular cellulose acetate membranes with a porous fibre reinforced plastic tube as a backing material has been developed. The FRP tubes were developed by the National Aeronautical Laboratory, Bangalore. Further work on non-cellulosic polyamide membranes is in progress. A 10 $m^3$/day plant to serve as a demonstration unit to supply water in villages is being fabricated by the BARC for the Gujarat Water Supply and Sewerage Board.

A small RO unit of about 1 $m^3$/day was supplied to the Gujarat Electricity Board by BARC for field trials. Another small unit of 0.7 $m^3$/day with high product recovery coupled to a windmill was supplied to College of Engineering, Guindy, Madras.

A manually-operated RO unit of 1 $m^3$/day has also been developed by BARC for use in rural areas where no electricity is available. A manually operated unit of 0.7 $m^3$/day capacity was fabricated at BARC for demonstration at the International Trade Fair at Delhi.

Electrodialysis (ED). The cation and anion exchange membranes to be used in the ED stacks have been developed by CSMCRI. The membranes posess good electro-chemical properties with a good degree of efficiency. Among the items developed have been suitable stacks consisting of gaskets and spacers made from plastic material; end electrode housings; and suitable channels for flow of solutions. A demonstration-cum-utility plant of 0.6 $m^3$/day capacity was installed and operated for a year at Motagokharwala village near Amreli in 1973 and later at Diu and several other places to treat brackish well waters.

The Defence Laboratory at Jodhpur has experimented with a plant of 10 $m^3$/day for drinking water with eight hours of operation. The component of these plants are available indigenously and commercialization of the plant through the National Research Development Council is under way.

The solar stills are very expensive and face the hazards of being broken by vandalism, storms and cyclones. However, in areas where no electricity is available, they would appear to be a good solution.

The RO and ED processes do need electricity and therefore, they are applicable only in areas where electricity is readily available.

It would appear from cost considerations that these two processes could play an important role in the country's crusade to supply potable water to villages which are now obliged to drink brackish water. The manual RO units have their limitations in that it may be difficult to find a volunteer to operate the unit or to employ a person specifically for this purpose.

Comparatively large-scale plants based on the thermal process could be located near power stations where steam is available. Apart from meeting the power station's needs, such plants could also meet the requirements for drinking water from the nearby population.

Cost Estimate for 10 $m^3$/day (8 hours operation)
Electrodialysis Plant

| Item | Cost (in Rupees) |
|---|---|
| ED stacks with stand and distribution panel | 160,000 |
| Rectifiers | 30,000 |
| Pumps | 22,500 |
| Flow meters | 30,000 |
| Filter, acid doser and softener | 30,000 |
| Salinity meter with cells | 15,000 |
| Sub-total | 287,500 |
| Contingency | 30,000 |
| Total | 317,000 |

Cost Estimate for a 10 $m^3$/day (8 hours operation) Reverse Osmosis plant

| Item | Cost (in Rupees) |
|---|---|
| Pre-treatment Unit | |
| (a) Filter with pump | 25,000 |
| (b) Water softening unit | 20,000 |
| Filter water storage tank | 35,000 |
| Chemical Dosing System with 2 dosing pumps | 10,000 |
| High pressure pump with motor | 20,000 |
| Reverse Osmosis Plant including pressure vessel, rubber lining, coupling, end plate, stand, high pressure houses, control panel, reverse osmosis tube or spiral modules, labour for membrane preparation | 120,000 |
| Post-treatment equipment--Decarbonator and air blower | 15,000 |
| Misc. RO Plant equipment | 15,000 |
| Potable water storage | 15,000 |
| Plant monitoring equipment | 10,000 |
| Sub-total | Rs 285,000 |
| Contingency | Rs 30,000 |
| Total | RS 315,000 |

The running costs will have to be based on actual experience of the installed plants.

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## E. Mexico: Water desalination experiences

by Oscar Perez Siller*

### 1. Potential areas for desalination application in Mexico

Mexico has a surface of almost 2 million $km^2$; according to climatic conditions, its territory may be classified as 67 per cent arid and semi-arid and 33 per cent humid. An important part of the population is settled in regions where because of altitude, soil or climatic conditions, fresh water is scarce. The combination of the above mentioned facts, combined with the availability of brackish or sea water along the coastlines (about 10,000 km of littoral) and the presence of economic resources (mainly fishing, tourism, mining) which need to be fully developed, makes water desalination a valuable non-conventional water resource to be exploited.

Except for off-shore drilling platforms, the availability of energy in the form of oil or gas does not physically coincide with the need to use desalination. This is particularly true in much of the Gulf of Mexico region where the largest amount of water and energy (oil) resources are present. In most other regions where fresh water is scarce, solar energy is available at an acceptable level but perhaps not used to its fullest extent.

There are some other regions where natural fresh water resources are being depleted (Continental Baja California Gulf and Caribbean Sea Coasts) because of extensive exploitation of ground-water resources and where desalination may be appropriate. In summary, the alternative represented by desalination may be a competitive one in extensive regions of north-west Mexico, certain areas of the north and the south-east of the country. All together these areas represent about one-sixth of Mexico's total surface.

### 2. First Desalination Plants in Mexico

Desalination for municipal fresh water supply purposes started in Mexico in the late 1960s, when the Federal Commission of Electricity installed two MSF distillation units of 14,000 $m^3$/day each in its Rosarito Power Plant in order to augment the fresh-water supply to the city of Tijuana in north-west Mexico. At that time, those units were some of the largest in the world. The Navy also installed some small solar distillation plants for the supply of fresh water to islands in the Pacific Ocean. The University of Sonora, in a joint project with the University of Arizona, built a solar plant for experimental purposes.

### 3. Federal Government desalination plants for fresh water supply

In 1971 the Commission for the Utilization of Saline Waters (CAAS), was created within the Federal Government structure as part of the Water Resources Ministry in order to design, build, install and operate desalination plants.

In 1976 as a result of a Federal Government reorganization, the commission was transformed into the General Directorate of Utilization of Saline Waters, later to include Solar Energy (DIGAASES), which was part of the

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Human Settlements and Public Works Ministry. In 1982, the general directorate was eliminated in order that in 1984 the Instituto SEDUE could be created. Among the functions that the Instituto SEDUE performs relate to the utilization of saline waters; the institute is within the structure of the Urban Development and Ecology Ministry.

During all of these changes the functions of these three organizations have remained substantially the same with an exception now in the area of actual plant operation. The function of plant operation has been transformed into giving advice on plant operation to state governments. This is because the ownership of existing desalination plants has been transferred to state governments in line with the general policy of decentralizing the Federal Government.

We think that the concept of designing, building, installing and operating the plants provides elements which enable us to perform better each of those actions than if we were specialized in one of them (Buros and others, 1980).

Since 1971 about 65 single-purpose service or experimental plants have been installed with capacities from 15 to 1,000 $m^3/d$. These plants are located in the Baja California Peninsula where they mainly supply fresh water to fishing villages or tourist resorts; in north-central Mexico they provide fresh water to agricultural communities; and in south-east Mexico they supply fishing or tourist communities. In three islands of the Pacific Ocean, plants have been installed to provide naval detachments and a penal colony with fresh water.

The processes selected have been reverse osmosis for brackish water, using either hollow fibre or spiral wound membrane configurations and mainly distillation processes for sea-water desalination. The distillation processes have included vapour compression and multi-stage flash, the former with more units installed and the latter with larger installed capacity. There are, however, some reverse osmosis units using either hollow fibre or spiral wound membrane configurations which are being used for sea-water desalination. For very small and isolated communities (up to 100 inhabitants), solar sea-water stills have been used to supply fresh water for human consumption. Additionally, there are some demonstration examples of small capacity (10 and 20 $m^3/d$) MSF distillation plants using flat and concentrating solar collectors to provide thermal energy. There is another example of a small brackish water RO plant whose electrical energy is provided by a photovoltaic field. All these examples are the result of joint projects with the Government of the Federal Republic of Germany.

Most plants are installed in isolated locations where erection is troublesome and where the supply of fuel, chemicals and spares required for operation is difficult. In these places there is also a scarcity of qualified personnel; therefore villagers are selected from the village and trained, since, given the isolation of the villages, it is difficult to move qualified people into them.

In the areas of installation and operation of sea-water desalination plants, difficulties are very often found in sea-water intakes where, except in a few naturally-protected locations, waves, sand or seaweed frequently impair plant erection and operation reliability.

Concerning MSF distillation plants, where transport or the absence of qualified people for building represent major difficulties, the concept of independent stages has been used, which apart from other advantages, allows for shop fabrication and hydrostatic testing of every stage and facilitates the transport, handling and erection of the evaporator (Sanchez Mejorada and Perez Siller, 1976).

Up to now, the installation of desalination plants has been financed by the Federal Government; however, owing to the country's present economic situation, it is intended that financial participation from state or municipal governments or from the villagers will have to be obtained for new desalination plants and their operation.

The process of installing a desalination plant starts with a written request from the villagers or state authorities to the Institute SEDUE stating that they are willing to co-operate in the desalination plant erection and/or operating expenses. Then a feasibility study is performed in order to decide whether desalination is the most appropriate method and to define the plant's size, process, location, main components, etc. Then the project phase follows when the detailed design and cost estimation of every component are considered, including in some cases the desalination equipment or specifications.

When the required budget is allocated, the erection and building phases are performed. The project is completed when the plant is commissioned, operators are trained and the plant's property is transferred to state authorities. Due to the difficulties mentioned earlier, this process may last up to four years. Guidelines to perform the above-mentioned feasibility study and project have been gradually prepared over the years and, if considered helpful to agencies in the desalination field of other developing countries, they could be translated into English and mailed upon request.

## 4. Other users of desalination plants

Regarding the total installed plant capacity and number of desalination plants in Mexico, the industrial use of desalinated water is more important than that for municipal applications (Instituto SEDUE, 1984).

The Government-owned Federal Commission of Electricity operates about 31 desalination plants to produce high purity boiler make-up water and two dual purpose units for municipal supply. Again, most of these plants are located in north-west Mexico and use the MSF process for sea water desalting. The rest of the industrially-oriented plants are in the north-central part of Mexico and use RO for brackish water desalting.

PEMEX, the national oil company, operates about 62 small sea-water desalination plants for human fresh water consumption or off-shore oil platforms or ships; they are mainly vapour compression, waste heat, submerged-tube evaporators and RO plants.

Private industries, mainly in the chemical, automotive or electronics fields, in the north and north-east use brackish water RO desalination. Bottled water, soft drink and beer companies in several parts of Mexico also use brackish water RO desalination. There are about 31 privately owned plants. Finally, some partially state-owned industries in the fields of steel manufacturing, mining or fish processing have installed about six sea-water or brackish-water desalination plants.

Another application for RO desalination technology is being initiated by the municipal government of Mexico City as a part of an experimental advanced waste-water treatment facility; if the results are positive, the facility will be expanded and its effluent used by industry.

## 5. National capabilities in desalination

Desalination plants using the various processes have been manufactured to a lesser or greater degree in Mexico and all of them are operated by Mexicans. Design capabilities are present in the Instituto SEDUE and in some private engineering firms.

Manufacturing capacity for MSF evaporators is available in several places where power plant equipment is fabricated. In fact, as a result of the governmental policy of import substitution, some local manufacturers have signed license agreements with major foreign desalination firms in order to offer MSF plants to the power-generating industry.

Some reverse osmosis plants are partially fabricated in the country, since key components such as permeators and high pressure pumps are still imported before assembly of the plants. Vapour compression plants are a similar case, in which vapour compressors were imported in order to fabricate two demonstration plants.

## 6. Criteria employed for process selection

The relative importance of criteria employed by Instituto SEDUE and its predecessors in selecting which desalination process to use for fresh water production has changed during the years, depending mainly on political or economic circumstances. For brackish-water desalination, the prevailing criteria have been plant reliability and minimum capital and operating costs. In the beginning, considering foreign experience and afterwards confirmed by the Institute, the criteria have led in all cases to the selection of the reverse osmosis process, mainly using hollow fibre aromatic polyamide or cellulose triacetate membranes. However, with the aim of acquiring more experience with other membrane configurations, spiral wound and flat membranes have been used. Depending on the work load for a particular fiscal year, decisions were made on whether the plant was to be assembled in the Instituto SEDUE (or its predecessors), or purchased abroad.

In the case of sea-water desalination, selection has broader possibilities at the international level; however, for Mexican conditions the distillation processes have been more frequently used since our experience up to now has been that they are more reliable and easier to operate. Nevertheless, the performance of installed RO plants is being observed in order that this process may be considered in future selections.

In some cases MSF plants have been selected due to their potential to be locally manufactured. Vapour compression package plants have been bought abroad because of their relatively short delivery time.

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## F. Morocco: Experience in the use of desalination for water supply

by Houssain Abouzaid*

Morocco is situated in the north-west of Africa and has one coastline on the Mediterranean Sea and another on the Atlantic Ocean. About 83 per cent of the territory may be classified as arid, in the sense that total evaporation potential exceeds the total rainfall. Under current water planning programmes, there are only three river basins (Loukkos, Sebou and Bouregveg) in which the total available water resources exceed the total water demand. Those river basins represent less than 10 per cent of the country's territory. At the national level, the total resources that may be made available amount to 25 $km^3$/year, of which ground water represents 20 per cent. An additional 2 $km^3$/year may be added to the total, if brackish ground water is taken into account. It should be noted that in many localities of the southern part of the country, no other water resource than brackish water is available.

Some industries are using different demineralization techniques, mainly to enhance water quality for boilers; distillation, electrodialysis and ion exchange have been used for that purpose.

In Morocco, it was primarily the extension of water supply to the communities situated in the southern part of the country that led the Government to consider the use of desalination to meet the challenge. The first achievement in that field took place in 1963, when a small electrodialysis installation was used at Tarfaya to treat brackish water to supply that centre with potable water. Currently, four localities are supplied with desalted water and in a fifth (Smara), operation was scheduled to start in summer 1985. Many more localities are supplied occasionally by desalted water from mobile units. Nevertheless, the total amount of desalted water produced remains quite modest: about 36,000 $m^3$ in 1983 for all the units operated by the National Drinking Water Office. A summary of the desalination plants in Morocco is given in table 67.

As may be expected for a non-oil producing developing country, desalination remains a very expensive way to supply water. We have therefore developed a double distribution system to avoid desalination wherever possible or limit its use to a minimum where it is unavoidable. The system works as follows:

- brackish water is distributed in the network for all domestic needs other than drinking and cooking;

- desalted water is distributed via standpipes to ensure that 15 to 20 per cent of the total water supply is of potable quality.

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Table 67. Water Supply from desalination in Morocco

| Locality | Type of water | Process | Date of completion | Capacity ($m^3$/day) | Observations |
|---|---|---|---|---|---|
| Tarfaya | Brackish | ED | 1963 | 20 | Not in operation |
| | Brackish | ED | 1975 | 75 | Not in operation |
| | Brackish | RO | 1982 | 100 | |
| Boujdour | Sea | Mechanical VC | 1976 | 250 | |
| Tan-Tan Beach a/ | Sea | Thermal VC | 1977 | 125 | under extension |
| Mir Elleft a/ | Sea | Thermal VC | 1977 | 125 | |
| Smara | Brackish | RO | 1985 | 250 | Scheduled to start operation 1985 |
| Mobile Units | N.A. | Mechanical VC | 1976 | 75 | |
| | N.A. | Thermal VC | 1976 | 8 | About 20 units available |

Notes:

ED = Electrodialysis
RO = Reverse Osmosis
VC = Vapour Compression

a/ Not operated by National Drinking Water Office (ONEP)

Experiments with this system have been carried out at Laayoun, a city of about 95,000 inhabitants, where:

- 100 l/s of brackish water (6,000 to 9,000 ppm of total dissolved solids) are distributed in a network of 100 km total length.

- 20 l/s of good quality ground water is distributed through 27 standpipes.

This dual system is now under implementation in Tarfaya, Boujdour and Smara. Due to the small size of the desalting plants, their situation in small centres and the high variation in water demand in the localities supplied by desalted water, the operation costs are quite high. Costs were distributed as shown below in 1984 for the units operated by the Drinking Water Office:

| Item | Brackish Water ($DH/m^3$)[a] | Sea Water ($DH/m^3$) |
|---|---|---|
| Energy (generated on the spot) | 5 | 19 |
| Chemicals | 0.5 | 1 |
| Maintenance | 0.5 | 1.5 |
| Labour and overheads | 0.2 | 0.2 |
| Total | 6.2 | 21.7 |

[a] $US1.00=Dirhams 9.75 (April 1985).

At April 1985 exchange rates, the total operating costs were $US0.64/m^3$ for brackish-water desalination and $US2.23/m^3$ for sea-water desalination.

A master plan is now under preparation for the water supply of all pre-saharian and saharian parts of the country. For that purpose, the following four different methods of supplying water are being considered:

(1) Local development of water resources through an extensive programme of ground water exploration.

(2) Transportation of water from the north to the south by developing a long-range feeder network.

(3) Desalting of locally-available brackish and sea water.

(4) Transportation of water by tankers from the northern part of the country.

## G. Saudi Arabia: Twenty years of desalination

by Daud Solaiman Khumayyis*

### 1. Background

Saudi Arabia is one of the countries that depends heavily on the use of non-conventional water resources, and desalination of brackish and sea water has been the method adopted so far.

The Kingdom realized that the scarcity of natural fresh-water recources was an important constraint to development, and thus an office or a department in the Ministry of Agriculture and Water was founded in 1964 which was responsible for investigating the possible use of sea water as a source of fresh water. This Department expanded to become the Deputy Ministry for Desalination, and in 1974 the Saline Water Conversion Corporation (SWCC) was founded by Royal Decree.

This governmental corporation has a specific responsibility to build, operate and maintain desalination plants where needed so as to provide an adequate and reliable water source. The Corporation has a central office in Riyadh, the capital, and two regional branch offices: one in the Eastern Province of Saudi Arabia (Gulf Coast) and the other in the Western Province (Red Sea Coast).

SWCC is headed by a governor with three deputies. The different departments, Projects, Construction, Research, Training, Finance, Administration, and others, are each headed by a Director General. In addition, each of the two branch offices is headed by a Director General.

When the Kingdom started to be interested in desalination and realized that it was a solution to the water problem, the first plants were built. The start was very strong, two small single purpose MSF plants of 62,000 gpd were built in two small localities on the Red Sea. The two plants were operational by 1968. In 1970 came Jeddah phase I, a dual purpose facility with a 5 mgd MSF desalter connected to a 50 MW power generation plant. On the Eastern coast two plants were also built. Both were single purpose MSF desalting plants: Al Khobar phase I (7.5 mgd) and Al Khafji phase I (125,000 gpd). They were both operational by 1973.

Construction of plants continued and by 1985, 15 plants on the Red Sea and 4 on the Gulf were operational with a total water production of more than 500 mgd and electricity generating capacity of over 3,000 MW. The activity of SWCC expanded tremendously to include serving not only coastal locations, but also inland sites. Madina, located over 190 km inland from the Red Sea Coast, and Riyadh, the capital, more than 460 km inland from the Gulf Coast, are already drinking piped distilled water.

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In methods of project execution, considerable progress has been achieved. SWCC qualified Saudi engineers are now taking a more important and involved role in defining the requirements to the consultants, reviewing alternatives, selecting the most suitable and appropriate proposal, and getting involved in detailed specification preparation, taking into consideration the vast acquired operating experience. During construction projects, a team of SWCC Saudi engineers is given the responsibility in the field, along with the consultant, to monitor and certify the quality and quantity of work executed by the erection contractors.

In the field of plant operation and maintenance, SWCC has gone through a gradual transfer of responsibility. The first plants were operated and maintained completely by contractors, without any involvement of SWCC staff. The next step was to second Saudi engineers and technicians to the operation and maintenance (O and M) contractors to get training and obtain some experience. Then SWCC took over the O and M responsibility but, due to an insufficient number of Saudi engineers, made arrangements with qualified O and M contractors to hire on a secondment basis some of their men to fill in the vacant top plant management positions. Finally now the complete O and M responsibility has been assumed by SWCC. Direct hiring is taking place without involvement of any contractors.

Currently 60 per cent of the total O and M staff are Saudis and the percentage is continuously rising due to the availability of graduates from the two SWCC training centers.

## 2. Technical experience

During these 20 years of plant operation a lot of technical experience was achieved. The old but large MSF Jeddah I and Al Khobar I produced considerable real field operational data. These two acid-dosed plants with their inherent problems reflected the history and the evolution of the existing decisions and achievements.

It is valuable to list some of the design problems below.

(a) Loose steam properties and conditions and high top brine temperatures led to scaling of brine heaters.

(b) High $O_2$ content in make-up and brine recycle streams led to a high rate of corrosion of the shell and the internal parts of the plants.

(c) Improper material selection also enhanced other types of corrosion.

(d) Improper attention to simple but important design parameters such as sea water salinity and its potential fluctuations, led to improper chemical treatment and thus it was impossible to achieve design production capacity.

Operation and maintenance was generally poor, owing to lack of proper supervision from the client. Also the idea of having a contractor completely responsible for operation and maintenance resulted in less expenditure, because of the commercial nature and attitude of the contractor, which deprived the plant of required maintenance. These problems resulted in a shortened life span of about 12 years for the above-referenced plants.

The lessons learned were as follows:

(a) Proper attention should be given to material selection;

(b) The use of external deaerotors to restrict dissolved oxygen to less than 20 ppb was necessary to supress corrosion;

(c) Top brine temperatures should be kept at less than 118$^{o}$ C if acid treatment is chosen;

(d) Chemical additives can be used for scale treatment where salinity is fluctuating;

(e) When using additives on-line, ball cleaning must be used to increase the running period before acid cleaning;

(f) During both the design and the plant operation stages, strict control on allowable minimum brine recycle pressure is needed, in order to restrict boiling of the recycle feed in the brine heater tubes.

## H. Somali Democratic Republic: Solar desalination experience

by A.I. Aden*

### 1. Data on Somalia

Area: 640,000 $km^2$

Population: 5 million

Location: Between Latitude 12° North and Latitude 0°5 South (Map 7).

Climate: Hot and Dry; average temperature in winter ranges between 23°C and 27°C in the south and between 18°C and 20°C in the north. In summer, the range is from 30°C to 37°C in the north and from 25°C to 26°C in the south.

Average Rainfall is 250 mm per year, except in certain southern regions where the rainfall can exceed 300 mm and in the north along the Gulf of Aden, where the rainfall is under 100 mm. There are two rainy seasons, one in spring and the other in autumn.

Hydrology. There are two permanent rivers: Juba and Shabelle. High humidity, together with strong hot winds, results in high evaporation rates which exceed the rainfall at many places in Somalia. Widespread occurrence of evaporation sediments, low rainfall and high evaporation rates are responsible for a high concentration of salts both in surface and ground water in Somalia.

### 2. Somali experience with non-conventional water resources (Solar sea-water desalination)

It is common knowledge that the escalating costs of imported oil products constitute a heavy burden on the already poor economy of Somalia.

To alleviate this apparent constraint to development, the Government embarked on a programme of introducing low and medium cost technologies utilizing renewable energies such as solar, wind and biomass.

Experiments and research projects on solar energy are carried out by a number of countries in Europe, Asia, Africa and America. Somalia is among the countries that has contributed to the promotion and harnessing of solar energy. The sea-water desalination (distillation) pilot plant installed and currently operating at Kudha Village is situated in Badhaadhe District of the Lower Juba Region; it was first established as a result of settling displaced fishermen from islands of the Kismayo Coast.

In early 1976 a fishing community of 300 families took root there. The objective of this radical move was to improve the social and economic well-being of those long ignored islanders. Immediately it was realized that lack of potable water could impede their social progress.

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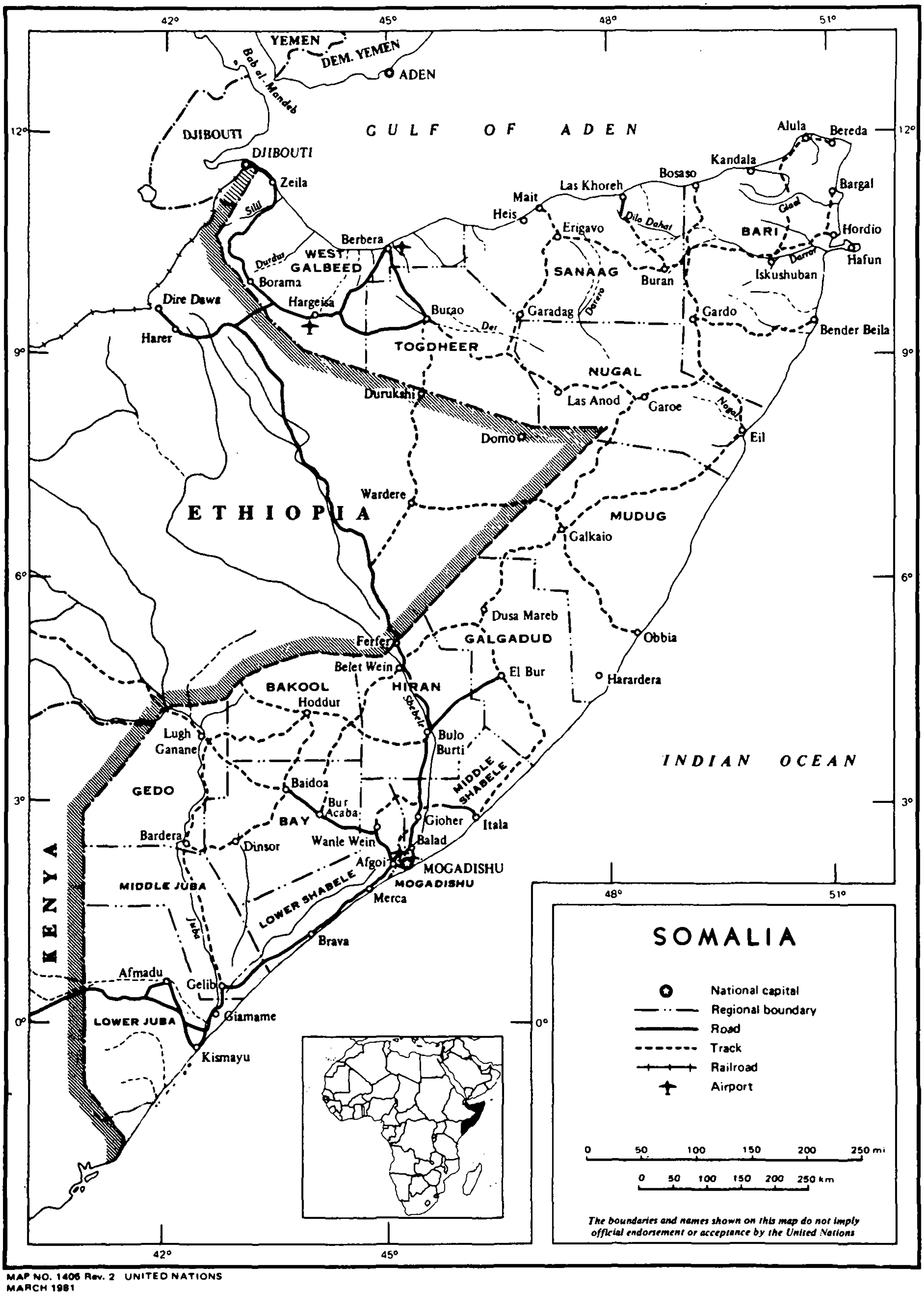


Map 7. Somali Democratic Republic

To remedy the situation, the Ministry of Mineral and Water Resources dispatched a survey team composed of Ministry officials and others from automous organizations such as the Water Development Agency to explore ways of providing water to the community. In this effort a systematic search providing hydrogeological reconnaisance, geophysical investigation and drilling was implemented. This preliminary survey failed to produce the desired result. After having exhaused ground-water possibilities, other options were examined. Sea-water distillation came to mind and multilateral and bilateral aid donors were approached.

The United Nations Childrens Fund (UNICEF) and the United Nations Industrial Development Organization (UNIDO) responded, resulting in a project for which UNIDO supplied the plant design and other information, while UNICEF provided the materials and supplies not found locally. The Somali Government has carried out the implementation of the plant. In 1979 three solar still units, the salient prototypes, were constructed, each having dimensions of 12.30 m by 1.14 m.

The purpose of performing this experiment was to observe the productivity of the prototype before constructing a full-size plant. Each isolated unit provided 40 litres/day and, according to the design parameters, the whole plant would have produced an average of 5,400 l/day, an amount far surpassing the original production level foreseen by the UNIDO experts.

### 3. Kudha plant elements

The pilot plant consists of 15 blocks (each of 12.75 m by 12.66 m) of 9 solar still units each, thus totalling 135 solar stills (see figure 48).

There are also three storage tanks with different capacities, as follows:

(a) Raw sea-water tank (feeding tank) (capacity 20 $m^3$).

(b) Rain water/distilled water tank (capacity 225 $m^3$) constructed under ground level.

(c) The overhead reservoir for supplying the village (capacity 17 $m^3$).

During the rainy seasons when clouds reduce solar radiation, the channels placed at the edges of the glass roofs of stills also collect rain water, which is subsequently stored for community use. This measure ensures the availability of water to village in most circumstances.

### 4. Solar desalination process

There is no doubt that an energy saving effect can be obtained if solar energy can be ulilized to desalinate sea water. It is very meaningful to utilize solar energy for sea-water or brackish-water desalination to supply fresh water to residents of isolated islands and desert areas where solar heat is abundant, but water supply falls short of demand such as in Somalia.

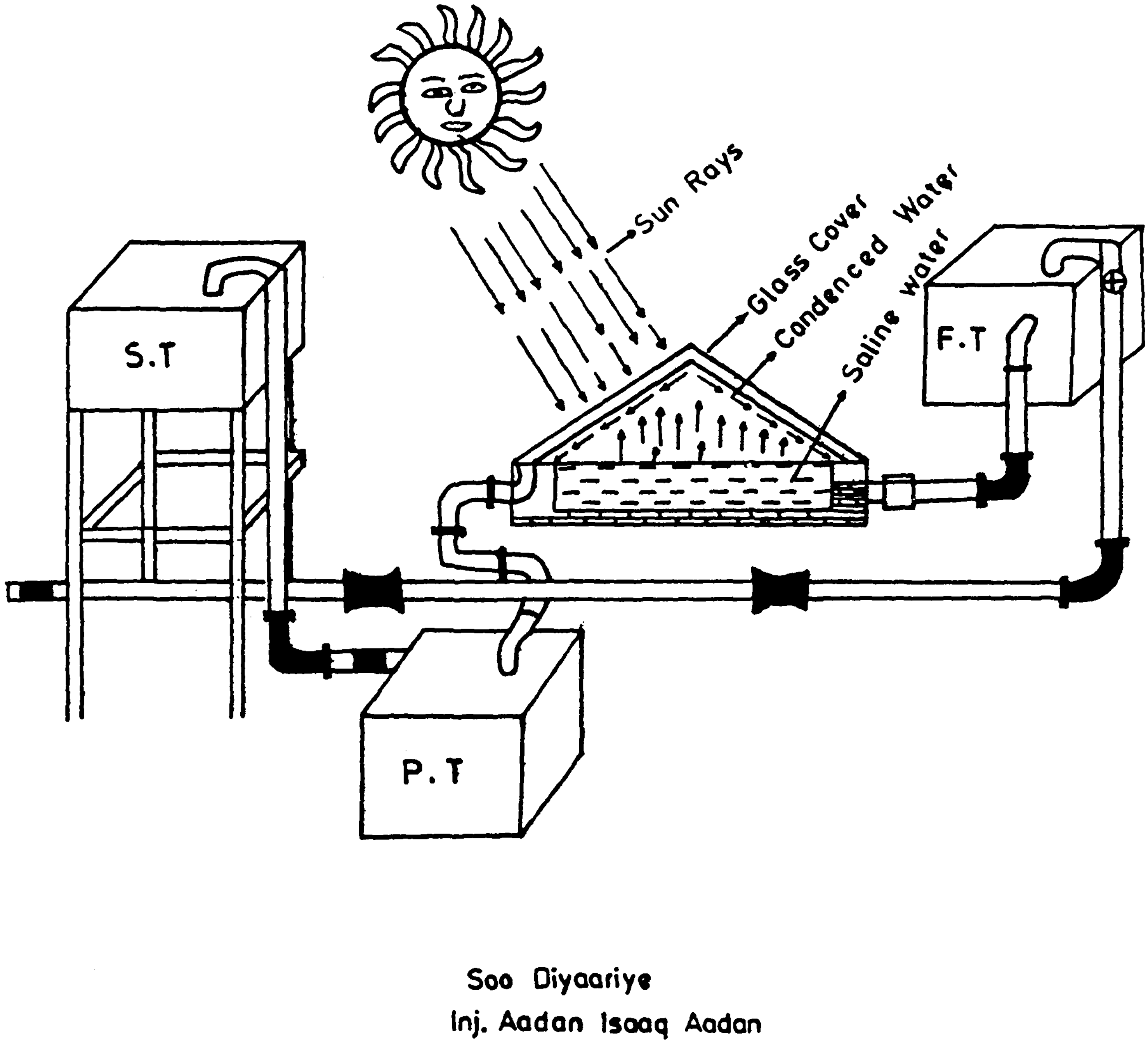


Figure 48. Solar distillation plant in Kudha, Somalia

At present however, the introduction of the solar desalination process entails a number of problems. First, the plant is not easily operated by the residents of the area requiring water. Second, the plant still requires some improvement in terms of stability and reliability. Third, spare parts, corrosion and maintenance are problems. The average annual temperature in this area is 25°C and radiation is 525 $Cal/Cm^2/Day$.

## 5. Summary

The direct method of Solar desalination has been used since 1979 in Somalia. The direct method uses a basin type solar still for direct distillation of sea water with solar energy. A pilot plant with an area of 3,600 $m^2$ was installed at Kudha Village for a population of about 2,000 persons.

## III. EXPERIENCES WITH TRANSPORTATION OF WATER BY TANKER

### A. Antigua

by S.A. Blackman*

#### 1. Brief description of Antigua

The water resources of Antigua are limited by its small size, topography, geological formation, natural salinity of some of the geological strata, and the variability of the rainfall pattern across the island.

Antigua has an area of 108 square miles. Seventy per cent of the island is below 100 ft in altitude; 96 per cent is below the 500 ft level and only one per cent of the land is over the 1,000 ft level. The highest peak, Boggy Peak, rises to 1,319 ft. All the peaks over the 1,000 ft level lie in the southern part of the island. That part of the island is of volcanic origin.

The northern and eastern parts of the island are generally undulating, limestone formations, rising to more than 400 ft in places. Between these two areas lies the central plain, which is mostly low-lying (below 50 ft), but which rises at a few points to almost 400 ft.

The usual temperatures in Antigua range from 73.1°F (22.8°C) to 84.1°F (28.9°C). The average relative humidity is 77.3 per cent. The average rainfall is 44 inches (1,120 mm) per year, with average rainfall in the north-eastern part much lower than in the south-eastern part. Open water evaporation is 65 inches (1,650 mm) per year.

(a) General water supply situation

During normal conditions before the drought of 1984, the bulk of the island water supply was obtained from surface impoundments. The major source was the Potworks Dam, which was a storage capacity of some one million imperial gallons. Total capacity of surface impoundments is in the region of approximately 1.3 million imperial gallons. The balance of the water supply comes from wells. Those sources provided approximately 2.0 million imperial gallons per day (IGPD), with around 1.5 million IGPD supplied from surface catchments.

(b) Water supply situation in 1983/1984

Following a year of less than average rainfall in 1982, Antigua's water supply situation grew steadily worse as only 22 inches (560 mm) of rain were received during 1983. By the end of the year the surface water reservoirs had begun to dry up and to create serious concern. This dry spell continued in 1984 and in the first four months of that year only a total 8.32 inches (210 mm) of rain had been received. As the situation grew steadily worse, it became impossible to maintain any water supply from our surface impoundments. By March of 1984 the primary remaining source of potable water was the 500,000 IGPD from ground-water sources.

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As a result of this worsening situation the government of Antigua was forced to declare a national disaster and to seek international assistance in coping with the water shortage. In late March/early April, four donor agencies, the British Development Division (BDD), the Canadian International Development Agency (CIDA), the European Development Fund (EDF) and the United States Agency for International Development (USAID) responded positively to this request. In mid-April the barging of water to the island commenced.

2. Facilities for receiving barged water into Antigua

While water had not been barged into Antigua prior to the 1984 drought, several points of the distribution system were close to the coast and were considered as possible points for the receipt of barged water. These points included the Crabbs Peninsula, the High Point Dock, the Saint John's Deep Water Harbour and the main beach hotels.

The Crabbs Peninsula was the site of the abandoned Antigua Public Utilities Authority (APUA) desalination plant. At this site and still in usable condition was a 2.5 million gallon welded steel tank, which had been previously used for the storage of production water from the desalination plant. This tank was about 200 ft from the shoreline, but the water about 250 yds off-shore was only about 14 ft deep. On the inlet side of the tank the piping was, prior to the decision to barge water, connected to the lime conditioner associated with the old desalintation plant. When it was decided to barge water, this piping was replaced with an eight-inch diameter line running towards the shoreline and ending some 10 ft or so from the water's edge. On the outlet side of the tank there were two pumps which had the capability of pumping water through a 12-inch diameter line to the Parham Pump Station or to the Scotts Hill or Cedar Valley reservoirs for distribution into the system.

The next major alternative site for receiving barged water was the High Point Dock. This dock is located about 5,000 ft from APUA's Coolidge reservoir. This reservoir has a capacity of approximately 530,000 IG. Water in this reservoir is pumped into a small section of the total distribution system. In order to make this point suitable for receiving barged water, it was necessary to place a suitable pump on the dock and to run a new six-inch line from the pump to the reservoir. The third alternative considered by the APUA was the Deep Water Harbour. At that point water can be pumped straight into the distribution system through existing four and six-inch pipelines.

While the APUA was not involved in the barging of water to hotels, several of those institutions were in the process, at about the same time, of making private arrangements for the barging of water to their facilities. The condition and ease of pumping barged water ashore to these hotels differed from place to place.

Because of the significance of the availabale storage at Crabbs and the possibilities for pumping water into most parts of the system, Crabbs was chosen as the main reception point. High Point, treated as a secondary reception point, was used to receive water for the small area it served.

## 3. Experiences while barging

In order to execute the required barging exercise the APUA obtained the services of two private organizations. One of them had several years of experience in the transportation of water from island to island in the Caribbean. The company had several tugs and barges of various sizes at its disposal, and had an arrangement with the authorities in Guadeloupe for supplying of water for shipment overseas. Inasmuch as the company was solely committed to the water transportation business, its barges were more than adequately equipped with the necessary pumps and hoses required for off-loading. Additionally, the methods for determining the quantity of water delivered followed a standardized procedure.

In contrast with the first company, the second company entered into the water transportation activity because they had to transport some equipment on the deck of their barge to Antigua at about the same time as the barging activity was getting started. Since the additional barging capacity could be utilized and, having ascertained that the barge had not previously been used to haul any harmful cargo, the second company's services were also engaged after the government of Antigua had made arrangements with the Government of Dominica fro the supply of water.

The quantities of water barged into Antigua during the five-month period that it was carried out were 21 million IG by the first company and 5 million IG by the second.

The first company utilized two barges of 575,000 IG capacity and one of 750,000 IG capacity. The second company's barge was of 1.1 million IG capacity. Only the two smaller barges operated by the first company were able to deliver water to Crabbs, because of the limitation imposed by the depth of the water off-shore and the hose available. Whenever the first company's larger barge arrived, it would dock at High Point but load its cargo into a smaller barge for off-loading at Crabbs.

The cost of this water delivered to Antigua was $US 24.00/1,000 IG. The off-loading time for one of the 575,000 IG barges was in the region of eight hours. The time for one of these barges to leave Crabbs, go to Guadeloupe and return to Crabbs was three to four days.

Before each shipment of water was received, APUA personnel tested for colour, pH, and chlorine residual. The quality of the water supplied by the first company was always found to be completely acceptable. On occasions the water in some of the tanks of the second company had to be rejected. On one occasion when the second company did go to Guadeloupe to pick up a shipment, oil was accidentally pumped into one of its holds. However, after cleaning, that tank was tested for signs of oil contamination and found to be clean.

One of the areas the APUA personnel found to be of vital importance for the successful operation of a barging operation was that of communication. Communication by radio between ship to shore and between the pumping and receiving stations was very important for being able to plan for the arrival of a barge and to stop the barge pumping should a hose at sea or a pipeline on land fail or any other problem occur while off-loading. A small boat with a reliable outboard motor was very important for providing access to the barge for testing of water quality or for determing the quantity of water delivered.

Other items which the APUA personnel found to be of great assistance to ensure the smooth running of its barging operation were buoys to mark the channel and one to mark the location of its off-shore mooring. Proper fenders should also be provided for cases where barges are going to be tied up alongside a dock.

Additionally, agreement on a standardized procedure for use in measuring the quantity of water delivered is absolutely necessary.

Last but by no means least, operators should be chosen with great care and be throughly briefed because. despite the best plans, something can and will go wrong.

## Conclusion

APUA experience with barging indicates that it is a viable alternative and that given proper care and attention in the selection of the transporting company, and the proper planning of the activity, water can be provided at costs and flexibility which rival other non-conventional water resources options.

## B. Dominica: Caribbean experiences with transporting water by tanker

by S.C. de Haan*

The island of Dominica has become a source of water for export by tankers or barges since a facility for this purpose was recently constructed on the island.

Transport of drinking water by tankers or barges in the Caribbean is not new, as can be seen from the following examples:

(a) In the Bahamas water is barged from the island of Andros to Nassau;

(b) In Curaçao water has been or is still imported from Rotterdam;

(c) Water was exported from Dominica to St. Martin before September 1979; the operation was discontinued after hurricane David, and then resumed recently;

(d) Aruba imported water from Dominica in 1984 during a period of six months;

(e) Antigua imported water from Dominica and Guadeloupe during water shortage problems in 1984.

It is clear that in the Carribbean Dominica is a main producer of water for transport by vessels. Dominica is the largest of the English-speaking Windward Islands and is located between the French islands of Guadeloupe and Martinique. The island measures 47.5 km from N to S and 27.4 km from E to W and has an area of 750 $km^2$ (see map 9). The population of about 75,000 lives mainly near the coast with the highest concentration of about 25,000 in and around the capital of Roseau. The island is of recent volcanic origin; it still counts several hot and warm springs and has a boiling lake. The island is very steep and mountainous and a range of peaks can be distinguished along the centerline of the island with the highest one of Morne (Mne) Diablotin measuring over 1,400 m (4,600 ft) and others like Mne Trois Piton, Mne Macaque and Mne Anglais ranging from 1,120 - 1,370 m (3,683 - 4,500 ft). The major area of the Central highlands is national forest reserve consisting of dense rain forest, the lower slopes being partly used for cultivation.

The prevailing moist trade winds from the Atlantic Ocean are forced up the steep slopes, resulting in high rainfall. From the rainfall pattern over the year, a wet season from June to January and a dry season from February to May can be distinguished. However, it appears that the dry season is hardly "dry" because the rainfall is still considerable. Therefore, Dominicans say that during the dry season it rains regularly and during the wet season always.

In the centre of the island the average yearly rainfall is around 9,000 mm and the over-all yearly rainfall is about 4,900 mm which averages to about 13.5 mm per day. So Dominica receives on the order of 3,660 million $m^3$ of rain per year, which is about 10 million $m^3$/day or 116 $m^3$/sec average. Without doubt Dominica's rainfall is abundant and is one of the highest on earth.

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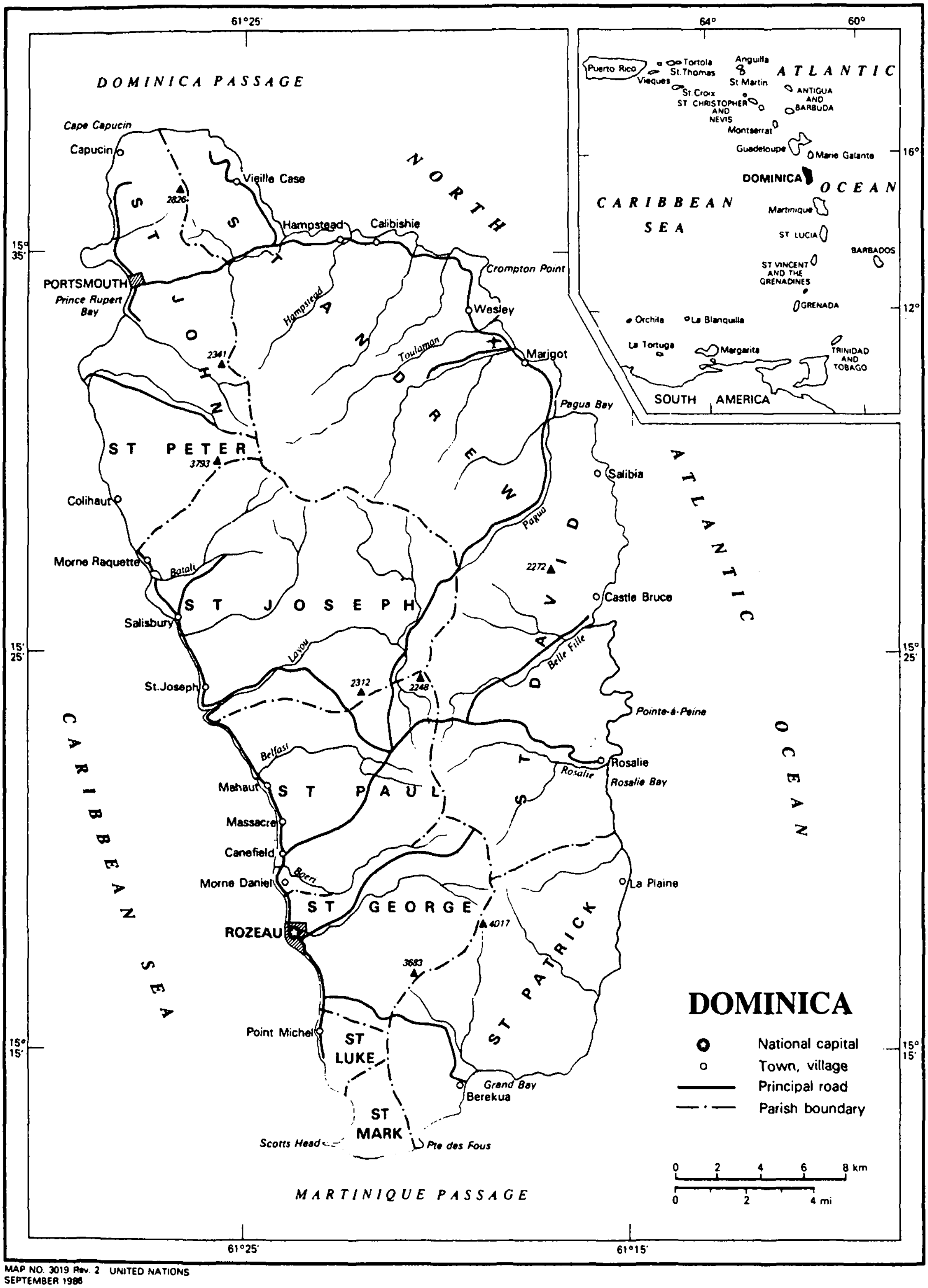
*Central Water Authority, Dominica (W.I.).




Map 8. Dominica

In the past it was commonly believed that in Dominica there were 365 rivers, one for each day of the year. In the 1960s a study was done in which distinction was made between defined and undefined drainage areas. A defined drainage area has a river system with a single well-defined outlet to the sea and an undefined drainage area has no river system but a general overland surface flow to the sea. According to that definition, 271 defined and 271 undefined drainage areas were counted.

As sources for transport of water, only the larger drainage areas will be of interest and therefore the defined drainage areas of over 1,000 ha have been identified for this purpose. The major drainage areas are centred on the principal mountain peaks of Mne Diablotin, Mne Trois Piton, Micotrin and Mne Anglais, which are mainly part of the national forest reserve. Water from these drainage areas is therefore of excellent quality and hardly needs any treatment for drinking.

The largest drainage area is of the Layou River with an area of 7,608 ha and the second largest is of the Castle Bruce River with an area of 4,043 ha. The majority of the rivers drain off at the north, east and south coasts of the island. However, because of prevailing east winds, rough seas and shallow depths, loading of tankers on these sides is extremely difficult. Therefore, only rivers along the west coast are of interest for this subject.

Unfortunately, hydrological data for most of the streams are very limited or non-existent and the following figures of estimated flows are only indications.

Estimated minimum flows:

Picard River 62,000 $m^3$/day (will also supply public system in future)
Bataka River 53,000 $m^3$/day
Layou River 160,000 $m^3$/day (90 per cent dependability)
Springfield River 28,000 $m^3$/day (el 333 m)
River Claire 36,000 $m^3$/day.

For loading, vessels need to be berthed as near as possible to the shore to make the length of floating hoses or expensive submarine pipelines as short as possible, and to protect vessels against prevailing winds and waves. Along the west coast the fathom (36 m) depth line is not further than 1,100 m from the coast, while near Roseau the 20 fathom depth is only a few hundred metres from shore.

Up until now, for the export of water only the Layou River and the drinking water supply system of Roseau and vicinity have been studied as possible sources; water from the latter is now being exported.

For the Layou River, plans have been made by the International Water Resources Ltd for export of water to Saudi Arabia with very large crude oil carriers taking fresh water as ballast and load on their return trip. Under the direction of that company, in September 1981 Century Engineering issued a study proposing an extensive plan consisting of a hydro-electric scheme as an optional facility.

In the same study a rapid deployment plan was proposed consisting of interim loading facilities which could be constructed within a few months. Special consideration was given to use these proposed facilities for loading dedicated vessels for transport of water to islands in the Caribbean.

The following are facilities for export of drinking water which are at present in operation on Dominica.

The source for these facilities is the drinking water supply system of Roseau and surrounding areas. The whole system operates by gravity. From an intake on the Checkhall River at elevation 333 m the water goes via a pipeline to a treatment plant consisting of sedimentation and chlorination. From the treatment plant a supply main supplies the different separate distribution systems in the coastal area between Mahaut and Pointe Michel through reservoirs or break pressure tanks.

From this supply main a lined earth wall reservoir located on Mne Daniel is fed and from this an eight-inch diameter pipeline runs to the jetty of Roseau's deep water harbour. From the manifold on the jetty a barge or tanker which is berthed at the jetty or anchored off-shore, can be loaded via hoses. The capacity of this system is 4,500 $m^3$ per day which can be loaded within 8 to 10 hours, depending on the size, length and number of hoses.

From January untill July 1984, this system supplied 4,500 $m^3$/day to the Public Utilities in Aruba during the period that one of their desalination plants had broken down. Because the water from their remaining desalination plants was needed for the operation of the local Exxon refinery, that company was also involved in the water export operation by transporting water in their tankers, namely the Esso Tampa of 38,000 tons and the Esso Shimizu of about 30,000 tons.

Loading one of these tankers took 7 to 9 days. To enable normal operation to continue at the dock, anchoring off-shore appeared to be necessary and two six-inch diameter floating hoses were used for loading the vessel. The pipeline on the dock was casted into a protecting concrete layer and the hose was partly sunk to allow movements of small ships over it so that normal dock operation could continue unobstructed.

Both tankers used were furnished with bow propellers, enabling them to manoeuvre into anchoring position without the assistance of a tug boat. They were berthed by the ship's anchors at the bow and by bollards on shore. Because of the resumption of operation of the desalination plant and lower production at the Lago oil refinery, deliveries to Aruba were discontinued in July 1984. On the other hand, delivery to St. Martin of about 4,500 $m^3$ every two days had resumed.

In their report to International Water Resources, Ltd, the Bechtel Group gives some estimates of transportation costs of potable water with barges and tankers. The costs of fresh-water transportation depend on several factors such that a definite cost estimate cannot be made without more detailed information.

The most critical variables are:

(a) Distance between loading port and discharge port;
(b) Controlling water depth and mode of transport used;
(c) Matching volumes and tankerage for full equipment utilization; and
(d) Timing and duration of project.

Estimated transportation costs for fresh water from Dominica ($US/m$^3$)

| Available mooring depths | Nearby Islands (50 to 150 miles) | Medium Distances (300 - 600 miles) |
|---|---|---|
| 6 m (partly loaded barge) | $1.80 to 2.60 | $3.60 - 5.65 |
| 7.5 m (full barge) | 1.40 to 2.00 | 2.75 - 4.35 |
| 8.5 - 10.4 m (nearly full 32,000 dwt) | 2.40 to 2.75 | 3.25 - 4.30 |
| 10.7 m (partly loaded 65,000 dwt) | about 2.00 | 2.50 - 3.30 |
| 12.2 m (nearly full 65,000 dwt) | about 1.60 | 2.00 - 2.70 |

Note: dwt: dead weight ton

In the case of backhaul transport of water from Dominica to any of the islands along the Venezuelan coast east of Aruba, costs are summarized below. This example is for full cargoes of fresh water, which will need treatment if used for drinking water.

Estimated transportation costs for backhaul tanker movements from Dominica to south-east Caribbean (full load)

20,000 - 40,000 dwt tankers $US 2.45/m$^3$
40,000 - 80,000 dwt tankers $US 1.70/m$^3$
80,000 - 160,000 dwt tankers $US 1.25/m$^3$

Marine water barging or tankering is an expensive option for augmenting water supply, but with currently escalating energy prices, it becomes competitive with desalination. Water deficient islands of the Caribbean, especially those whose economy depends on a reliable water supply for tourism, should consider import of water by tankers as a viable option.

Besides the Layou and the Checkhall Rivers, several other sources for export of water are available some of which could be easily developed. One example is the hydro-electric power scheme in the Roseau Valley.

On Dominica hydro-electric power is used for base supply while diesel plants cover peak demands and stand-by operations. Water from fresh water lakes in the national forest reserve is used for a hydro-power plant at Papilotte, where the water from the tailrace of the plant is added to water taken from the Roseau river which is piped to the power station Padu. The tailrace from this station is on average 128,000 m$^3$/day and as a minimum 30,000 m$^3$/day. There are plans to increase the capacity of this scheme, after which the average flow will be 244,000 m$^3$/day and minimum 58,000 m$^3$. However, these plans are only in the study phase. From the tailrace of the Padu electric power station, a gravity system could be made to the bay front at Roseau for export in barges or smaller tankers.

## Conclusions

1. The cost of marine barging is competitive with desalination and should be considered as a viable option by water deficient islands of the Caribbean.

2. Dominica has several sources for water export of good to excellent quality and sufficient quantity.

3. The possible use of gravity makes cheap operation of loading systems possible.

4. Sufficient depths allow berthing near the coast at several places.

5. Besides the studies mentioned, other possible sources should be studied for their feasibility.

## C. Mediterranean area: Experiences with shipping fresh water

by F. Bonifacio*

The experience acquired in shipping fresh water throughout the Mediterranean is of recent date but invaluable. This is probably the very first time in the world that such tonnages of water were shipped from one port to another.

The water exporting operation took place between mid-August and mid-November 1983 and involved shipping 1,300,000 $m^3$ of fresh water by tanker out of Marseilles harbour to Tarragona in Spain for the EMPETROL Refinery (Empresa Nacional del Petroleo). This venture was the outcome of project studies and other factors that might be of interest when this operation is compared with traditional tanker shipping.

First, there were two actors involved in the operation, the Port of Marseilles Authority and the Canal of Provence Authority. The Port of Marseilles Authority (PMA) is a State-controlled Authority with financial independence entrusted with managing the Port, which comprises the Eastern Harbour Area (i.e., Marseilles Harbour) and the Western Harbour Area, comprising Lavera and Fos.

The Port of Marseilles is ranked sixth in the world. The Industrial Zone of Fos managed by the PMA is one of Europe's largest, comprising facilities such as refineries and a very effective modern steelworks. In view of the experience and know-how gained by the PMA in running such an Industrial Zone, the Port Authority is also an Engineering Company that studies and supervises the construction of ports in many parts of the world.

The Canal of Provence Authority (CPA) is also a public agency entrusted with providing industry, farmers and urban areas with their water requirements in the South of France. CPA have also been entrusted with building a canal to pipe water into the area from the Alps. CPA is also in charge of managing and running the canal on behalf of the Government.

The practical experience gained by CPA in this field has enabled it to perform project studies and development projects in rural and urban hydraulics in many areas of the world. In conjunction with other French companies, CPA has founded one of the most important engineering firms specializing in hydraulic applications worldwide.

The Provençal region of southern France has a hydraulic network providing considerable amounts of water of excellent quality, in addition to having a port capable of accommodating any size of vessel afloat and whose oil traffic is second only to Rotterdam.

In view of the facilities available to both Authorities, they soon realized the potential of shipping fresh water. Initial studies were conducted jointly with a French refining company which wanted to use its tanker fleet to ship fresh water on the ships' return journey from Fos to

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ports in the Middle East. The study had to be abandoned, although the idea was attractive, because of several obstacles. The most serious difficulty was that this type of traffic needed to be very regular between the import and export ports; currently the traffic is not regular, because of the glut in the oil market. Also, the water importing port would have to be an oil exporting port. Other difficulties were cited in a recent study conducted by the Japanese. Since the situation is likely to change from one period to another, close contacts are still being kept with operators interested in this kind of trade.

The PMA and the CPA have not abandoned the idea altogether but would prefer a shuttle service, which would be organized as deemed appropriate by all concerned. Negotiations could be initiated to consider matters such as water quality and quantity, conditions of sale, duration of the supply contract and the guarantees offered by the suppliers for a regular, durable and available supply of water.

The PMA and the CPA can guarantee regular supplies for a commodity as essential as water, and sailings can be worked out for any destination whether it is an oil-exporting port or not. Thus, water would be dealt with as the main cargo being shipped and its cost would vary as a function of the price of water on board, harbour dues and freight costs. Freight costs are the only component that vary as a function of the distance the water is shipped. Sailings would therefore be limited in distance and the quality of water shipped would depend on the use to which the was is put.

Both the PMA and the CPA agree that water could be shipped out of Lavera and Fos for any port in the Mediterranean, the Red Sea and the West Coast of Africa as far as Mauritania. It needs to be borne in mind that one of the main advantages of using a dedicated vessel for shipping water is that the water will not be polluted with oil residue when it arrives at the port of destination. It is true to say that the quality of the water once it reaches its final destination may suffer slightly, however, owing to the transit times involved and especially if the water contained some organic matter or substances such as sulphates, phosphates and nitrates, when pumped on board the tanker. Such substances are likely to be found in water that is piped in from rivers, lagoons or boreholes located along the coast as a result of municipal, industrial or agricultural residues.

The water piped into the Port of Marseilles is from the French Alps and can be supplied all year long. The only limit in this case is the port's reception and storage capability and that of the vessels involved in the operation. Such were the considerations that had to be studied by EMPETROL when they had to shut down their refinery in Tarragona for want of water during a very dry spell in 1983. The EMPETROL refinery requires some 25,000 $m^3$ of a poor quality salty water. During the period in question, only 10,000 $m^3$ per day were available. In the light of the problem they had to resolve, EMPETROL looked into alternative supplies by rail, road and sea.

The only viable solution was to transport water by sea and no Spanish port was in a position to guarantee such huge quantities of water without running into political and social strife. This meant that Marseilles was the nearest port from which plentiful quantities of good quality water could be readily supplied. Turn-around times were of the order of 5 to 6 days which meant that the shuttle vessel had to be of the 100,000 dwt class in order to ship 15,000 X 5.5 = 82,500 $m^3$ of water on one voyage. Fresh water was also used to ballast the tanker in order to obviate mishaps such as contamination if ever the ship had to be ballasted with sea water on its return journey.

EMPETROL studied the situation thoroughly and realized that it could get ready supplies of good quality water from CPA. The PMA for its part ensured berthing priorities 24 hours per day 365 days a year which meant that sailings would be regular. EMPETROL then chartered the Billy Jeane A, a tanker of 92,790 dwt which, when thoroughly cleaned, started the shuttle service on 16 August 1983. It took the port teams 30 hours to load the Billy Jeane A at a rate of 3,000 $m^3$ per hour and the total time spent by the vessel in port for one loading operation was on average 35 hours with a turn-around time of 5 to 6 days, as the vessel could not moor at night in Tarragona harbour, where a storage tank had been set up to accommodate the cargo that would be distributed according to requirements of the refinery.

The quality of the water shipped to Tarragona did not vary at all during transport and when mixed with local water provided a better average mix. Adopting this kind of solution afforded EMPETROL with the possibility of not shutting the refinery down, honouring their contracts and keeping customers satisfied. This kind of operation when well-studied and performed ensured regular water supplies for the refinery up until mid-November when the rains started in Spain and in the Mediterranean as a whole, thus leading to abundant supplies in and around Tarragona capable of meeting the requirements of the EMPETROL refinery.

The same kind of situation will be encountered when considering urban water requirements. The only difference arises in that in this case water consumption is not constant. Demand increases during the tourist holiday season. Supply security will only become a problem when local resources fail to meet requirements, mainly during the hot spell in the summer months. At this point a fresh water shuttle service can be adopted to meet specific requirements. Other countries may have a water shortage all year long and the situation is made even worse in the hot summer months. In most cases this kind of problem is resolved by constructing desalination plants. If the distance involved is not too great, the shuttle service can be an attractive alternative to desalination, as no heavy capital outlay is required, supplies can be shipped very quickly and the service is a flexible one, which means that the vessel sailing can be geared to match local requirements.

Even if countries decide to build desalination plants, shipping fresh water can still be viable as an additional source of supply and not a competitor. In any case, the size of the desalination plant to be built will vary as a function of the demand for water now and in the future. The plant may thus be either too small, leading to shortages at one moment or another during the year, or else too large, which will then involve excessive per $m^3$ costs of water desalinated by the plant. It needs to be borne in mind that the marginal production cost for one $m^3$ of desalinated water rises steeply if the plant is not producing at its nominal capacity. In that case, the most appropriate solution would be to build a plant capable of meeting constant demand and then "topping up" with extra supplies when and where required. This is where the shipment of fresh water by tanker can be regarded as an interesting complement. In view of its flexibility, such a supply service would enable a country or region to face up to fluctuations in supply and demand from one year to the next and could be regarded as a back-up supply in the event of plant failures or shut downs for maintenance purposes.

Such has been the experience gained by the Canal of Provence Authority and the Port of Marseilles Authority in shipping fresh water. Both Authorities are prepared and quite willing to assist countries in finding solutions to resolve their water supply problems, especially when the problems are serious.

# IV. EXPERIENCES WITH RAIN-WATER CATCHMENT SYSTEMS

## A. Caribbean Islands: A review of roof and purpose built catchments

by Peter Hadwen*

### Introduction

For over three centuries, roof catchments and cistern storage have been the basis for a domestic water supply in many small islands of the Caribbean; during World War II, several airfields were turned into catchments, and there are instances of capturing urban run-off for agriculture, and using factory roofs for catching water for industrial use. Although roof catch systems have declined in some countries, it is estimated that 750,000 people in the English-speaking Caribbean depend at least partly on such supplies.

The optimal cistern size area has generally been assessed as 10 gallons/sq ft of roof area, but in drier or drought-prone areas, 5 gallons has been used. For public supplies, Martin-Kaye (1956) devised the following formula:

(a) Assess the minimum daily average per capita water use;

(b) Multiply by number of persons in house;

(c) Multiply by 100 to allow for 100 rain-free days;

(d) Subtract, less 10 per cent, the storage capacity of existing public cisterns;

(e) Add 10 per cent to the result to cover losses.

This gives the desirable size of cistern; for dry areas, the total can be divided by 5 to assess catchment area needed.

Some of the older and more elaborate systems were constructed at forts built by the French and British during Napoleonic times. Well-preserved examples are Brimstone Hill, St. Kitts, and Shirley Heights, Antigua; Prospect Hill Fort in Bermuda is still in use as a catchment, and the moat is being sectioned off to provide covered storage.

### 1. Catchment types

#### (a) Roofs

The majority of roof catch systems are of galvanized iron, both painted and unpainted. Some of the large older houses used imported slates and tiles because local rocks were unsuited for roofing. An important exception is Bermuda where specially cut and painted limestone has been used for years (Thomas, 1980).

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(b) Purpose built catchments

Because concrete is easily laid at relatively low cost, and materials are readily available in most places in the Caribbean, it has been the main material to create purpose built impervious surfaces. The quality of those has varied because of the kind of unskilled labour, and also because of:

(i) Unskilled labour;

(ii) The sand:cement ratio, and nature of aggregate;

(iii) The quality of make-up water; sometimes it is brackish or very sulphated;

(iv) Climate conditions at time of placement;

(v) Thickness of the cement layer;

(vi) Condition and nature of sub-soil, especially clay;

(vii) Manner of making joints.

These factors cause a variation in the efficiency of collection and the costs of maintenance. In-use concrete catchments are common in the Turks and Caicos Islands (TCI) and Grenadine Islands. They provided a domestic water supply for United States Naval facilities for 30-40 years in TCI, and in the Bahamas, where the fully amortized cost in 1977 was about $20/1,000 gallons, (including $0.04/1,000 gal running cost). Application of a cement slurry seal after 20 years operation was said to have increased run-off efficiency from 65 to nearly 90 per cent. Daily per capita needs ranged from 47-53 US gallons/day.

## 2. Country reviews

For all of the islands reviewed below, except Bermuda, actual pan evaporation is 65-77 in (1,650 - 1,990 mm); for Bermuda it is about 55 in. Most islands are either volcanic and mountainous, or are formed from limestone and with low elevation and relief.

(a) Anguilla

In Anguilla drought is commonplace. In 1971, several successful wells were drilled on which a piped water supply was based. The system is unreliable and private rain-fed cisterns continue to be the main water supply. In 1974, 58 per cent of dwellings had cisterns, rising by 1981 to 65 per cent. The remainder rely largely on roof-fed 44 gallon drums, and on public stand-pipes. Many houses having cesterns do not have roofs large enough to sustain supplies for families through dry seasons; purpose built catchments other than roofs do not exist, but in 1984 the Caribbean Development Bank agreed to finance the building of one.

Collection of rain from roofs is likely to continue in the foreseeable future because of preferred taste. Ground water usually has at least 500 ppm chlorides, and often contains sulphides.

(b) Antigua

Antigua is characterized by knobby volcanic hills in the south-west; a limestone plateau at elevations of 100 - 300 ft (30 - 100 m) in the east; and a partly clay-covered mixed volcanics-limestone zone in the central NW-SE area of Antigua. No permanent water courses exist. There have been frequent droughts; the following statistics are drawn from 100 years' records for Coolidge Airport.

| Consecutive years of below average rainfall | Incidence | Most serious cumulative deficit | | Annual Average Rainfall | |
|---|---|---|---|---|---|
| | | Inches | mm | Inches | mm |
| 2 | 5 | 19 | 482 | | |
| 3 | 6 | 29 | 737 | | |
| 4 | - | | | 43.25 | 1,100 |
| 5 | 2 | 36 | 914 | | |
| 6 | 1 | 60 | 1,524 | | |

From 1910 to 1930 above average rainfall was recorded in only five years. There is considerable variation in monthly rainfall, partly because of cyclones; about half the total rain falls during August to November, the hurricane season. Water supply is based on springs, dug wells and roof catchments; there is a long history of poor water availability. Dams (1.3 mgd) and more than 70 drilled wells (1.0 mgd) are used for public supplies. However, ground water in some areas is brackish. In the early 1940s, the United States Air Force largely overcame water shortage problems by collecting water from the airport runway, invaluable in the 1984 drought.

Martin-Kaye (1954) described collecting rain from roofs and storing in cisterns as commonplace. At the Mill Reef resort, concrete catchments were constructed to provide the total supply. Many hotels still collect roof water, and in the mid-1970s the Antigua government seriously considered introducing legislation requiring new properties to collect and store rain water. Most houses with larger than 1,500 $ft^2$ roof area collect and store water, but this practice is not encouraged by existing legislation.

Purpose built catchments formerly were quite widespread, and several are marked on the 1:50,000 map of 1977. Except on the off-shore islands, they are mostly out of use. The old military installations on the hills overlooking English Harbour were all designed to catch and store rain water.

Antigua has a serious problem of water supply, whether for domestic, agricultural or industrial use. Demand is barely met at present; with hoped-for increases in tourism, irrigation and industry, there is a very good case for harvesting rain water, at least for non-potable purposes. Antigua has one of the most adverse combinations of natural assets as regards water resources, ample justification for introducing rain-water collection by whatever means.

(c) Bahamas

Although 60 per cent of the population lives in New Providence, some 26 islands are inhabited to a major degree. Rainfall averages 60 in (1,524 mm) in the north, but is only 25 in (635 mm) in Great Inagua, the most southerly in the chain. Water supply is a problem; due to the smallness or shape of the islands, fresh ground water is not always present. Eleuthera, for example, is over 100 miles (160 km) long, but most of it is less than 2 miles (3 km) wide.

Roof and purpose built cathchments are commonplace, such as the one at the former United States Naval Base on Eleuthera. One settlement (Whale Cay) has a piped distribution system based on roof caught water. In New Providence, most of the older houses collect roof rain water and store it in cisterns averaging 15,000 gallons (70 $m^3$). Many are now dilapidated and polluted. One four-storey condominium collects roof water and most of the ground floor is given to storage tanks. Industrial use of roof-caught rain water is also practised, and a preliminary assessment has been made of using Nassau International Airport as a catchment (Janssens, 1978).

Two other kinds of systems have been taken to the pilot stage. On New Providence's south coast an aquavoir was constructed (Humphreys, 1971). This involved placing a plastic membrane into 15 to 20 ft circular trenches, later backfilled to attempt to form an artificial fresh-water lens. A 3 to 5 ft (1 to 1.5 m) lens formed but high sulphide content made the water unusable.

Adjacent to Nassau Airport runaways, an artificial aquifer was constructed by excavating to a depth of 5 to 8 ft (1.5 to 2.8 m) an area of 10,000 sq ft (930 $m^3$) and lining it with plastic sheet. It was then backfilled over a layer of gravel, to act as a reservoir for runway run-off water. Mainly because of excess scarifying, the artificial aquifer so produced had poor permeability, and there were leaks in the membrane (Colorado State University, 1981).

Surveys have established the extent and potential of all major fresh water lenses, and public supplies depend entirely on ground water. Where public supplies are not provided, roof and purpose built catchments are likely to remain the sole source of potable water. Improved methods of collecting and storing water are highly relevant to the Bahamas. The high cost of public water in New Providence means that increased collection from roofs is desirable, if not essential.

(d) Barbados

Barbados has enjoyed a good water supply for generations, and has an island-wide piped public water supply system, to which 90 per cent of the estimated 62,000 houses are connected. Only larger properties at elevations greater than 200 ft and built 100 or more years ago made provision for roof catchment and storage. In the future, catchments do not have a place in water supply; low-cost water storage is of interest to municipal and agricultural sectors, and the lining of large existing quarries might be feasible.

(e) Barbuda

Barbuda is 27 mi north of Antigua. Until the early 1970s, Codrington was the only settlement; in 1969 only 15 to 20 per cent of house roofs were equipped to collect water (British Army, 1969). Existing water supply facilities were described as rudimentary (Sparkes, 1974), with about 33 per cent of the population having access to roof-collection rain water, the remainder dependent on poor quality water from dug wells in karstic limestone.

In Barbuda the operating/managing of engineering works is likely to continue to present problems. In the future, roof-caught water will remain important, though for the poor, the cost of providing adequate storage will be a burden. A public supply based on ground water is the most viable, but the taste of rain water may be preferred. A number of depressions are naturally capped with fairly impervious rock, and easily could be converted into catchments.

(f) Belize

Belizean households have always collected from house roofs and stored rain water in cisterns. Recently this was done to satisfy basic needs, and to comply with a 1958 Public Ordinance which obliges house owners to collect and store rain, and which provides for penalties for non-compliance. In most cases, rain water is for potable use; for other purposes, water is derived from shallow wells. Financial constraints limit the size of the cisterns, and most private supplies are unable to cope with prolonged drought. Other water sources have to be resorted to every dry season. To alleviate this, the Government constructed rain-water storage facilities in rural communities, especially in the off-shore islands and coastal areas. The 50,000 gallon concrete cisterns collect rain water from their galvanized corrugated iron roofs and those of adjacent public buildings such as a school or community centre. They are brought into service only when private supplies have been depleted. Water is then rationed during the rest of the dry season, each householder being allotted a few gallons per day (Gonquez, 1980).

A number of limestone islands (Cays) 20 to 30 mi off the coast occur in two main groups - the Turneffe Islands and Ambergris Cay. Though originally inhabited mainly by fishermen, their beaches attract many visitors from the mainland where shores are overgrown with mangrove. The resident population is about 2,500. In these low-lying limestone islands, existing water supply is drawn mainly from roof catchments; ground water is being developed. While reasonably low in chlorides, ground water near the coast is high in sulphates, and on taste alone, roof-caught water will be the preferred supply for a considerable time to come.

(g) Bermuda

Bermuda consists of 120 islands, the main seven being linked by bridges. Most land is less than 1 mi wide. The country experiences a climate more temperate than for any of the Caribbean islands; water supply has been a problem in the past to the extent that cruise ships sold water to the authorities. A broad-based limited public supply system depends on ground water; on commercial desalination; and on collecting water from roofs and artificial catchments. All major hotels and some commercial and government premises use salt water for toilet flushing.

By law, every house must be provided with a roof catchment and cistern for which size averages 10,000 gallons; 80 per cent of every roof must be adequately guttered, or alternately, a similar area of artificially created catchment, feeding into tanks not less than 100 gallons per sq ft of roof. Catchments yielded an estimated 583 million gallons in 1980, an average of 1.6 million gallons per day (mgd). Thomas (1980), and United Nations (1964) described how cedar wood rum puncheons were used by the earliest settlers to collect and store water; later simple tanks were excavated in rock and made water-tight by lime cement and other materials. Distant from houses, artificial catchments were contrived by top soil removal and surface sealing. Bucket dipping prevailed before pumps were introduced, and consumption was based on what was available, or what could be carried. The installation of house cisterns began in the early 19th Century and many improvidents were dependent on neighbours. The Crown Lands Corporation, the United States Naval Base, Kindley Air Force Base, and a number of large hotels all constructed large hillside catchments. Water so collected was piped to dammed valleys or lined quarries. For instance, the Navel Base had a 14-acre catchment and a storage capacity of six million US gallons. The Castle Harbour Hotel built a 10 acre catchment with an adjoining reservoir of about four million US gallons.

The Prospect Hill catchment, formerly a fort, occupies several acres, and from its inception was a major supply source. It has a storage tank of one million gallons, and is capable of collecting seven million gallons in an average year. Sections of the original moat have been made into compartment storage facilities for the catchment, and for other supply sources.

The policy of enforcing roof catchments has been a limiting factor in public water supply development, especially until about 50 years ago. Since then, a limited distribution system based on other sources has developed. In the future, continued use of several water sources is envisaged but retention of the individual roof catchment system, together with brackish ground-water use for non-potable purposes, is seen as the continuing basis for Bermuda's water supply.

(h) British Virgin Islands

Only 16 of the British Virgin Islands (BVI) are inhabited throughout the year. Tortola, the main island, supports 86 per cent of the population and is hilly, with deep valleys cut into volcanic and intrusive igneous rocks. Droughts are common, with two to four months with no rainfall. Until 1977, there was no public water supply system and BVI depended largely on roof catch systems. For years, the tankering of water was the only government service to households whose system had run dry, at a cost of $US20/1,000 gal in 1979. Dug wells and occasional importation from Puerto Rico helped to relieve water shortages. The government used to have assistance schemes for installing private cisterns which often could not satisfy all household needs; many of the poorer dwellings were not suited to the purpose. Yet, although roofs of some government buildings caught rain water, some large buildings were not so provided. One 18,000 sq ft hillside catchment (on a $30^{o}$ slope) near Road Town was of defective construction. The reservoir has now been incorporated into the expanding supply system based on ground water. Current building regulations still require every property to collect rain on the basis of 10 gallons storage per sq ft of roof, but public properties are exempted. Discounting the hillside catchment, public rain-water cisterns had a storage capacity exceeding 170,000 gallons.

In the 1971 census, 64 per cent of dwellings had roof catch systems. These were extensively surveyed (Richards and Dumbleton, 1972). Cistern storage varied from 1,000 gallons (4.5 $m^3$) to 85,000 (386 $m^3$) for hotels; the average was 8,000 galls (36 $m^3$) and some of the larger cisterns were fed also from the mains. About 60 per cent were located beneath the house, the rest, mainly for larger houses, being under patios or the adjacent garden. A few old ones were stone lined, usually cement rendered; more recent ones were of cement block. Seventy-seven per cent of 169 householders preferred cistern water for all purposes; 60 per cent preferred it to mains water for drinking, and most neither boiled nor treated it. Existing regulations disallowed cisterns being sited near septic tanks, and no instances of pollution were found, but bacteriological tests indicated that only one-quarter to one-third were regarded as having quality acceptable to WHO standards.

Hotels and small industrial concerns were the first to realize that needs could not be met fully from roof catchments, even though they were collecting and storing as much as was possible. For example, in 1978 the three largest hotels each received in excess of 6,000 gpd through their public service connections. Since 1977, Roadtown and East End, have introduced limited piped supplies, which in 1984 reached 80 per cent of the rural, and the vast majority of the urban, population.

Water supplies in all other islands are still met wholly from roof catchments and cisterns and from dug wells. Experimentation in Virgin Gorda with desalination-power plants and solar stills was unsuccessful (United Nations, 1964).

Many customers have both cisterns and mains supply, with a preference for the taste of rain water. Because of fairly slow public water supply development, a long history of water shortages, and the legal need to provide a cistern for each house, rain-water catchments are likely to remain in use as a supplementary drinking water source for some years to come. As the public becomes acccustomed to the convenience of piped supply, use of roof catch water is likely to decline, but only as long as the cost of public water supply remains low.

(i) Cayman Islands

The Caymans comprise three islands - Grand Cayman (largest), Cayman Brac, and Little Cayman. Population has grown from 7,000 im 1960 to 17,000, and there are an increasing number of tourists (exceeding 150,000/year) and other transient residents.

Drought incidence is a problem. About 90 per cent of the rain falls in about seven wet months, and the contribution of cyclones to annual rainfall is in the range of 10-20 per cent but in some years may be nil. In the past, water needs were derived from roof catchment cisterns; this remains the most important potable source for domestic consumers, who use ground water when cisterns run dry. In a 1982 government survey, private households had the following water supply arrangements

| | Percentage |
|---|---|
| Cisterns only, based on roof catch | 19 |
| Wells only (dug and drilled) | 18 |
| Cistern plus well | 60 |
| No system | 3 |

To satisfy planning regulations, a house has to be provided with a cistern; this rule is relaxed where good ground water is available. Mather (1971) observed that a considerably increased quantity could be collected from much larger purpose built areas. In an earlier survey, Wallace Evans and Partners (1974) found that domestic cisterns as large as 20,000 gal were uncommon; low income persons were unable to afford a construction cost of $1 per gallon. The older hotels (20-30 rooms) have arrangements similar to domestic consumers, but most use sea water for toilet flushing. Collection of water from the airport runway was proposed by MacCallum (1969) but rejected by Wallace Evans (1974) on water quality grounds. The present policy is to develop ground water in three fresh water lenses (Beswick, 1983) and to expand desalination works.

Though much development of wells has taken place in Grnad Cayman in the last decade, there is still a preference for drinking rain water. Without doubt, roof catchments will continue to be used for some years, supplemented with fresh and brackish ground water.

(j) Dominica

Use of roof catchments for domestic supply has been declining throughout this century; by 1978, 78 per cent of the rural population was served by public stand-pipes. However, because of the extremely steep terrain, it is almost impossible for rural people living on ridges to fetch water from the valley bottoms and several thousand still collect roof water and store it in drums. Of all the small islands of the Caribbean, Dominica has perhaps the least need to develop roof or other impervious catchments, because of the abundance of other water supply sources.

(k) Grenada

A few catchments exist on older buildings of the mainland; their construction is not obligatory, and they are no longer used on a regular basis.

In Carriacou and Petit Martinique, many wells are brackish, and springs have poor yields; the islands depend heavily on public impervious catchments. In addition, most householders collect and store roof-catch water. Formerly, government loans were available to assist in adding gutters and cisterns to houses.

Martin-Kaye (1954) recorded a 100,000 sq ft public catchment with storage of 900,000 gal, capable of supplying 0.8 gal/day/year. There was no distribution; water was drawn from cisterns through stand-pipes. Many of the catchments and cisterns listed by Martin-Kaye remain in use. Collection of rain is likely to be the main water supply for the foreseeable future on both islands.

(l) Guadaloupe

Guadaloupe, a Department of France, consists of two main islands -- Grande-Terre (limestone), and Basse-Terre (volcanic). Abundant perennial streams and springs occur in the volcanic island and only a few older buildings collected roof water in cisterns. Grand Terre has no surface streams, and largely depends on ground water. Many older buildings still have roof collection and cistern storage, but these are becoming dilapidated and are used less. Guadaloupe also administers the islands of Marie Galante, Desirade, Isle des Saintes, part of St. Martin, and St. Barthomy. In all these, roof catchments are an important source of water supply, and are likely to remain so.

(m) Honduras

The islas de la Bahía (Bay Islands) off the shores of Honduras are fairly well developed for tourism. A substantial amount of their potable needs are derived from roof catchments, which will continue to serve as the main source of potable water supply.

(n) Jamaica

A survey carried out by Inter-Technology Services in 1973 showed that in three central parishes (mainly in limestone areas) 185 communities were using public rain-water tanks, and in most the rain catchment was the only water supply; these, together with privately-owned roof catchments and cisterns supplied the entire community's water needs. In general, cistern maintenance was poor, some being uncovered and a number not chlorinated.

In a more recent rural water supply study (Stanley/Joint Consultants, 1980), the continued use of roof and purpose built catchments was contemplated for all parts of rural Jamaica not having river, spring or drilled well supply sources. It was noted that communities were scattered, and had ill-defined boundaries, making it difficult to implement distribution systems. It is thought that more than 100,000 Jamaicans depend to a major extent on rain-water catchments. This is not surprising because in the areas covered by white limestone (70 per cent of the country), there is a total absence of rivers, and ground water is 1,000 ft or more below ground level, if it is present at all. Rainfall is 50 in and more. There are many natural hollows, which have been mined for bauxite and recontoured. Grouting or water-proofing of the fractured rock might be expensive, and membrane-lined catchments would be preferred. There is little doubt that roofs and cisterns will continue to provide the only water source for many rural dwellers. Experiments in Jamaica indicate that 10,000 gal steel reservoirs could be built at about half the cost of reinforced concrete (Inter-Technology Services, 1973).

(o) Martinique

Martinique has rugged volcanic mountains, abundant rainfall, many rivers, tropical rain forests, and is topographically quite similar to Dominica and St. Lucia. Although old military buildings and the largest country houses used to collect rain water from roofs, the practice has largely been discontinued.

(p) Montserrat

Most of the older large houses had provision for collecting and storing roof water. With the introduction of piped supplies, especially since the late 1960s, use of water from roof catchments has declined. The quality of water in some cisterns was bacteriologically unsafe and, in recent years there has been a desire to prohibit their use. It has never been obligatory to collect rain water from roofs in Montserrat.

Roof catchments still have a role to play in Montserrat. A fairly strongly-held government view is that roofs in the industrial park could satisfy certain agro-industrial needs (Hadwen and Pekurel, 1983).

(q) Netherlands Antilles

The three Leeward Islands of the Netherlands Antilles--Aruba, Curacao and Bonaire--are situated about lat. 12°N, just north of the Venezuela coast. The three Windward Islands -- St. Maarten, Saba and St. Eustatius -- are at lat. 18° N. The average precipitation of the Leeward Group is half that of the Windwards.

Roof catchments and cisterns formed the only water supply in all islands until 1910, when a distillation plant was installed in Curaçao. Since desalination became a major source of supply in 1928, roof catchments have ceased to be a significant supply in Curaçao and Aruba, and their use in Bonaire and St. Maarten is declining, especially in the main towns. In Saba and St. Eustatius, roof catchments and cisterns remain the main water supply, and are still important in St. Maarten, where most houses have suitable provision. In Saba, a concreted slope is used to collect rain water. With the small populations and remoteness of Saba and St. Eustatius, it seems likely that water supplies will continue to be based on ground water and roof catchments.

(r) St. Kitts/Nevis

In St. Kitts, ample spring flow has meant that roof catchments have never developed to a significant extent. The Brimstone Hill fortress built in 1680-1690 was designed to be self-sufficient in water by means of bricked catchment areas, silt sumps and cisterns. An increased pace of tourist development and unsatisfied agricultural demand could result in the reintroduction of catchments. The airport runway and condominium/hotel roofs in the dry south offer considerable potential.

(s) St. Lucia

Springs and rivers are common in the lush island of St. Lucia and although roof catchments used to be commonplace for the larger houses, they are now little used. Some villages on high ridges are not served by public supplies and roof water is collected. At some soft drink and beer bottling plants, warehouse roof rain water is used for washing and for some processing needs. It seems unlikely that roof-caught water will be of much importance in the future.

(t) St. Vincent and the Grenadines

Roof catchments are now little used in St. Vincent. Improved piped water supplies based on rivers and springs now supply almost all people. Catchments were common in the rural areas until the mid-1950s and remain the main source of water supply in the dry islands of the Grenadines. In a recent survey (Hadwen and de Jong, 1984), a poor state of repair was noted for most public roof and purpose built catchments. Although 35-50 gpd per 1,000 sq ft catchment is possible, the public supply is capable of providing about 2 gpd per person; only the poorer families with small houses do not collect and store water.

Bequia receives 10,000 visitors each year; hotels operate dual systems - roof catch and cisterns for potable uses, and brackish ground water for toilets/showers. There are two existing public catchments (one is out of use), with 232,000 gal storage, and one drilled well is operating. Numerous private dug wells also exist. Water is brought in from the mainland by tanker when the public reservoirs are low. In Canouan, about 9,100 sq ft of public catchment feeds into a 72,000 gal storage; one private catchment exists, and all the larger houses have roof catch cisterns. Mayreau relies entirely on private roof catch supplies; one hillside catchment supplies a hotel. Mustique also relies on private systems, and a catchment has been built around the airstrip, with an open storage reservoir. Palm has a 40,000 sq ft private catchment supplying a hotel. Petit St. Vincent had a solar distillation plant which is now derelict, and a roof catchment now supplies a hotel. Union Island has three public hillside catchments totalling about 40,000 sq ft, and supplying 435,000 gallons of storage. In addition, roofs of several public buildings are used. The Ashton catchment is built on a 33-36$^{\circ}$ slope.

Ground-water exploration may be fruitful but there is no doubt that hillside and roof catch systems will continue to be the basis of domestic water supplies in the foreseeable future.

(u) Trinidad and Tobago

Roof-catch systems ceased to be used to a major degree in the early 1950s in Trinidad except in certain rural areas that had unreliable public supplies. In Tobago, the opening of the Hillsborough Dam scheme in 1952 resulted in a rapid decline of roof-water collection.

(v) Turks and Caicos Islands

There are seven significantly populated islands, and in Grand Turk, where most of the population lives, there is no fresh ground water. The islands are very low lying, rainfall is low, and parts of some were turned into salinas, but are no longer used for salt production. Until 1983, domestic water supply in Grand Turk was entirely based on about a dozen purpose built catchments; government supplies are restricted to about 2 gal per person per day, and it is mandatory to construct a roof-catch cistern when building a house. The government recently took over two catchments and a desalination plant at former United States bases.

In some islands, limited fresh ground-water lenses occur; it follows that any householders intending to fully satisfy their water demand must depend on a combination of roof catch/storage and ground water, whether fresh or brackish. There are very few areas where fresh ground water can be pumped at more than 1 gpm without inducing saline intrusion.

Sparkes (1973) studied the extent to which local people could meet their water needs solely from roof-catch facilities. He found that an average galvanized iron (G.I.) roof (1,000 sq ft) was more or less capable of meeting a demand of 10 gal/head/day, depending on occupancy level. The condition of storage cistern, plumbing and guttering would of course determine the success. Sparkes also concluded that the purpose built or roof catchment system in Turks and Caicos depended on a few heavy storms each year, the occurrence of which were so random that statistical analysis was pointless; and that despite such constraints roof catch systems work reasonably well on 20-24 in annual rainfall. Water recovery (from G.I. roofs) was found to be consistently 85-90 per cent of the measured rainfall. He found that neoprene, hypalon, and other modern roof coverings perform even better, yielding run-off from heavy dew.

Currently water is neither treated nor tested; none of the 28 reservoirs in Grand Turk are inter-connected. A further 10 separate low-elevation systems serve the other islands. Improvements to correct problems are being devised, and the 10,000 ft runway is being studied as a potential catchment. In the foreseeable future, rain-catch systems will remain very important.

(w) United States Virgin Islands (USVI)

Until the introduction of desalination and barging of water from Puerto Rico, purpose built catchments averaging about five acres were widely used together with household roof and cistern arrangements. Most of the older houses were so equipped; such provision was mandatory for properties built in the last 30 years. By the early 1970s, most catchments were in an advanced state of neglect. The quality of water in private cisterns was poor, leading to some being condemned on grounds of hazard to public health.

Commercial water haulers still sell supplemental supplies to residents and small businesses, and most private individuals provide their own water supplies from rooftop catchments and/or wells. A 1980 comprehensive water resources management plan did not recommend continuance of rain-water harvesting using hillside and roof catchments because the cost was high]-- on the order of $25/1,000 gal, mainly for the cost of the cistern (Peebles, Pratt and Smith, 1979).

St. Thomas. About 20 catchments (0.5-5 acres) formerly existed of which 11 areas in the city (22.25 acres) were capable of yielding 21 million gal in an average year. The addition of more tanks and catchments was not considered feasible because of lack of space on this hilly island. Water from the reservoirs supplied public standpipes which were opened periodically.

In addition to the public supply sources, water is widely collected in private cisterns from roof catchments. TAMS (1958) reported 3,100 dwellings within the urban area provided with cisterns. However much of the roof area was inadequate to meet the occupants' annual requirements.

Potable water in rural areas is exclusively obtained from roof catchments. The total yield for rural and urban St. Thomas was estimated at 50,000 gal/day in 1960. A tank underlies the runway at Bourne airport, and catchment areas at the Submarine Base provided 9.45 million gal (35,800 $m^3$). Water from this source was filtered, chlorinated, and pumped into the distribution system up to 125 ft above sea level (United Nations, 1964). It is now disused.

St. John. A small paved catchment and cistern served the community of Cruz Bay through a few public outlets. Caneel Bay Plantation, a resort with rooms for over 200 guests, has a paved catchment with large cisterns, and roof catchments, supplemented by a sea-water distillation plant.

Two small concrete public catchments serve Bordeaux.

St. Croix. Five concrete hill catchments (0.1-1 acres) leading to roofed reservoirs used to serve the community. Individual house roof collection is still widespread.

The future outlook for USVI is that because only a small percentage of population is served by piped public systems, private roof catchments will continue to be essential despite a government decision to discontinue using hillside catchments.

(x) Venezuela

Eight small groups of islands occur north of the Venezuela Coast; all receive only 500-700 mm rain. Ground water is largely saline, and in all islands except Margarita, roof catch and cistern storage is a significant water supply source.

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## B. Kenya and Botswana: Experience with rain-water catchment systems

by H.J. McPherson and J. Gould*

### 1. Introduction

The last decade has witnessed a growing interest by international agencies and national governments in low-cost appropriate technology water systems as solutions to the water needs of the developing world. There have been several reasons for this. First, it has been realized that sophisticated technological solutions such as pumping systems and treatment plants often associated with a reticulated supply are simply not affordable by many developing countries either now or in the foreseeable future. Secondly, people are questioning whether high technology systems are the appropriate answer to the needs of the developing world - especially in rural areas where frequently there is no centralized government maintenance programme. Water systems have been failing at an alarming rate in developing countries. The usual reasons cited are: lack of proper operation and maintenance; problems in obtaining spare parts, usually from overseas; and the absence of skilled personnel who can make the needed repairs and undertake regular maintenance. Spare parts especially are a problem, as often governments are unwilling or unable to release scarce foreign exchange for their purchase.

The low-cost appropriate systems which are increasingly being built promise to provide water at low cost and, more importantly, they can be largely operated and maintained by the users themselves. This transference of some, if not most, of the responsibility for operation and maintenance to local communities greatly reduces the failure rate of systems.

In the water supply sector, the major low-cost technologies include hand-pump wells, gravity water systems and rainwater catchments. Wells equipped with handpumps exploit ground-water resources and are perhaps the most universal technology, followed by gravity water schemes. There are excellent examples of successful wells projects and gravity-water programmes in many countries. For example, the shallow wells programme in Livulezi in Malawi, the Lutheran shallow-well programme in Zimbabwe, the United Nations Childrens Fund (UNICEF) programme in Bangladesh and the Malawi and Nepal gravity-water schemes are a few of the better known projects. Rain-water catchment has tended to be the poor cousin of the appropriate water supply technologies and has been to a considerable extent ignored or neglected. However, in recent years there has been an increasing appreciation that rain-water catchment offers advantages over other systems and that in certain situations it may be the most realistic answer.

Rain-water catchments have been used in parts of East Africa for some time, and a considerable body of knowledge about rain-water catchment has accumulated. This paper proposes to describe experience with rain-water catchment in Kenya and Botswana. It will describe the current technology, the costs of the various alternative systems being constructed and the major advantages and disadvantages identified with rain-water catchments in East Africa.

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Definition. First, what is meant by rain-water catchment? A rain-water catchment is basically any systems which collects, stores and supplies surface rain-water run-off for human needs. However, because this definition could include such diverse systems as a puddle supplying livestock with drinking water to a huge hydro-electric dam project supplying the water and energy requirements of a whole nation, it is helpful to define these systems in a more precise way.

Although there is much confusion and duplication of the terminology dealing with the topic, rain-water catchment systems (synonymous with rain-water collection systems) normally refer to small-scale systems providing individual households or single communities with a primary or supplementary water supply. The term rain-water harvesting normally refers to the collection of rain-water from ground surfaces mainly for agricultural purposes. Confusion and misunderstanding about the exact meaning of this and other terms, seem to indicate an urgent need to establish a definite terminology on this topic. In this paper three main types of rain-water catchment systems will be described. These are:

(a) Roof catchments: systems for collection, storage and supply of rain-water from roof surfaces (figure 49);

(b) Rock catchments: systems for the collection, storage and supply of rain-water from untreated rock surfaces (figure 50); and

(c) Ground-water catchments: systems for the collection, storage and supply of rain-water from treated and untreated ground surfaces (figure 51).

All these systems consist of three components, a catchment area, a storage reservoir and an outlet for supply. In the case of rock catchment and roof catchment systems, the storage reservoir is normally above the surface and the water is supplied through gravity flow via a pipe or tap. For ground catchments, however, the storage reservoir is generally below the surface and some method for extracting the water is necessary, either directly by hand or using a pump.

## 2. Demand, supply and storage

The objective of a rain-water catchment scheme is to satisfy the required demand for water as efficiently as possible.

The demand for water can usually be determined fairly readily from a questionnaire survey, or a project design value can be estimated. Seven litres per day per capita is, for example, the minimum water requirement to support life. In many countries a per capita value of between 20 and 30 litres per day serves as a good indicator for daily water requirements.

Calculating the available supply and the size of the storage tank needed to meet the estimated demand is perhaps the most critical step in designing a catchment system. If the storage tank is built too small, the system will run dry and the users will become disenchanted. If the storage tank is made too large, this will greatly increase the costs and reduce affordability. It is therefore essential that an accurate estimate of the supply and the size of the needed storage tank be arrived at.

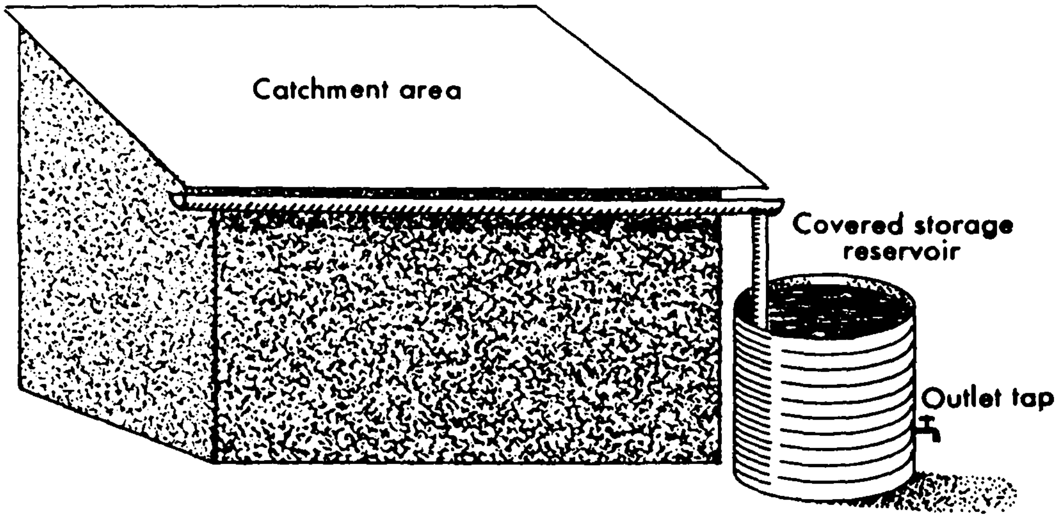


Figure 49. Roof catchment system

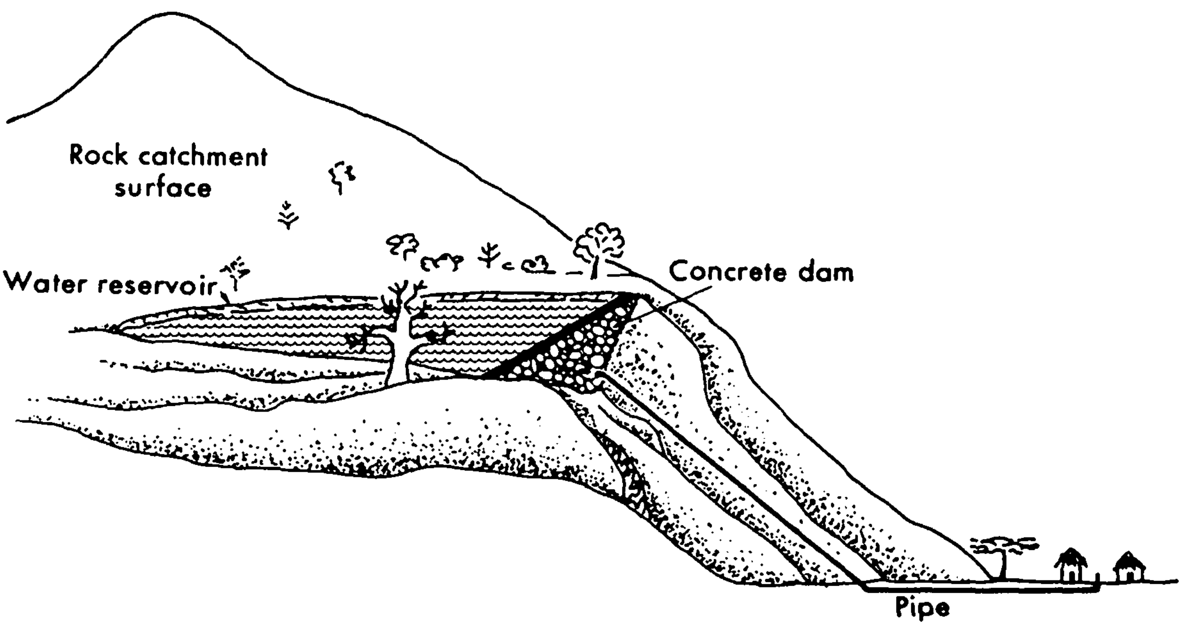


Figure 50. Rock catchment system

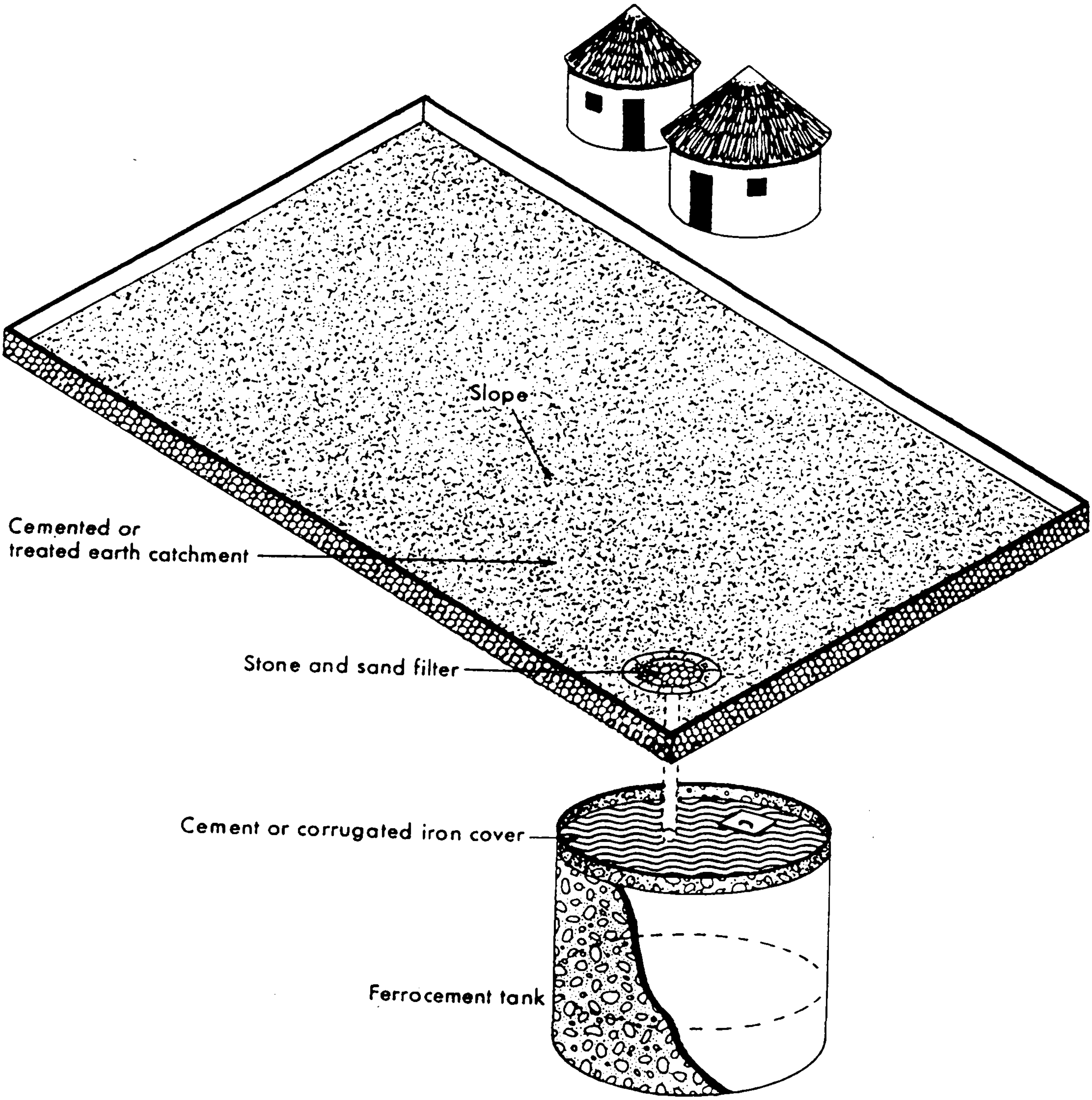


Figure 51. Ground catchment system

Two different values should be calculated for the supply. One for the total available annual rain-water supply is simply the catchment area multiplied by the mean annual rainfall multiplied by the run-off co-efficient. A second value should be calculated for the most economically feasible maximum annual rain-water supply. In order to do this, it is necessary to determine the supply which could be provided by different storage capacities and their costs.

A crude means of determining the storage capacity required for any particular rain-water catchment system is to determine the mean maximum length of the dry season (or mean maximum period without rain) and calculate the volume of demand over this period. This value is equivalent to the required storage.

Figure 52 illustrates the use of the graphical mass curve method for determining the storage requirements needed to provide a year round constant supply. The graph is produced by simply plotting the cumulative rain-water run-off (rainfall x catchment area x run-off co-efficient) against time and by placing the time representing the steady consumption of this water tangetially above the mass curve. Then the most critical (driest) period in the data can be identified and the storage demand estimated.

A more sophisticated method involves "critical period analysis" where the actual rainfall data for the particular locality are analyzed, and critical periods in the rainfall record identified. The storage requirement needed to overcome the most critical period can then be determined. Although this method is slow and laborious when done graphically or using a calculator, it can be carried out relatively simply and quickly with the aid of a computer. Computer methods for rain-water storage tank design have been developed by Perrens (1975) and Latham and Schiller (1984). The computer modelling approach allows considerably greater flexibility, as different levels of supply determined by percentage reliability of occurrence can be calculated for any given system (i.e., a given storage capacity collecting water from a known catchment area under a particular rainfall regime). Figure 53 shows the level of supply associated with any given storage capacity at 80 per cent, 95 per cent, 99 per cent and 100 per cent reliabilities for Mahalapye, Botswana. Both the storage and supply are given as fractions of the total useful run-off. Thus, a storage capacity equivalent to 0.4 multiplied by the total available useful run-off would supply 0.73 of this run-off with a 95 per cent level of reliability but only 0.49 with 100 per cent reliability. Put another way, this means that a 4 $m^3$ tank should yield 7.3 $m^3$ annually for 95 per cent of the time.

The computer modelling approach in essence provides a very reliable method for estimating an appropriate storage tank size for any given climatic situation at whatever level of reliability is desired.

## 3. Construction

The nature of the construction programme will obviously vary depending on whether a roof catchment, rock catchment or ground catchment scheme is being built. However, in all three an emphasis should be placed on building low-cost reservoirs where local inputs of labour and materials can be maximized.

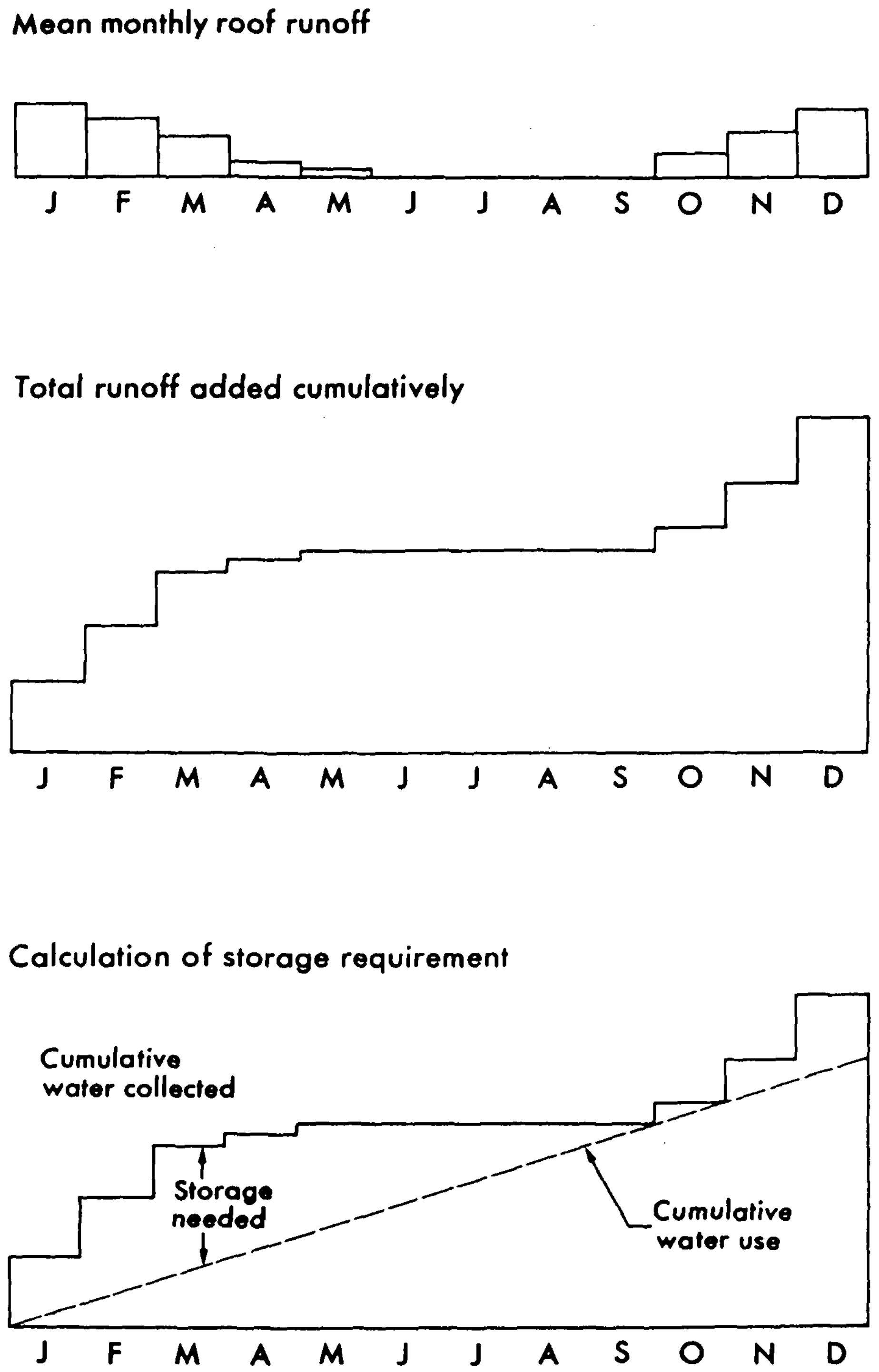


Figure 52. Simplified mass curve analysis for determining rain-water tank storage

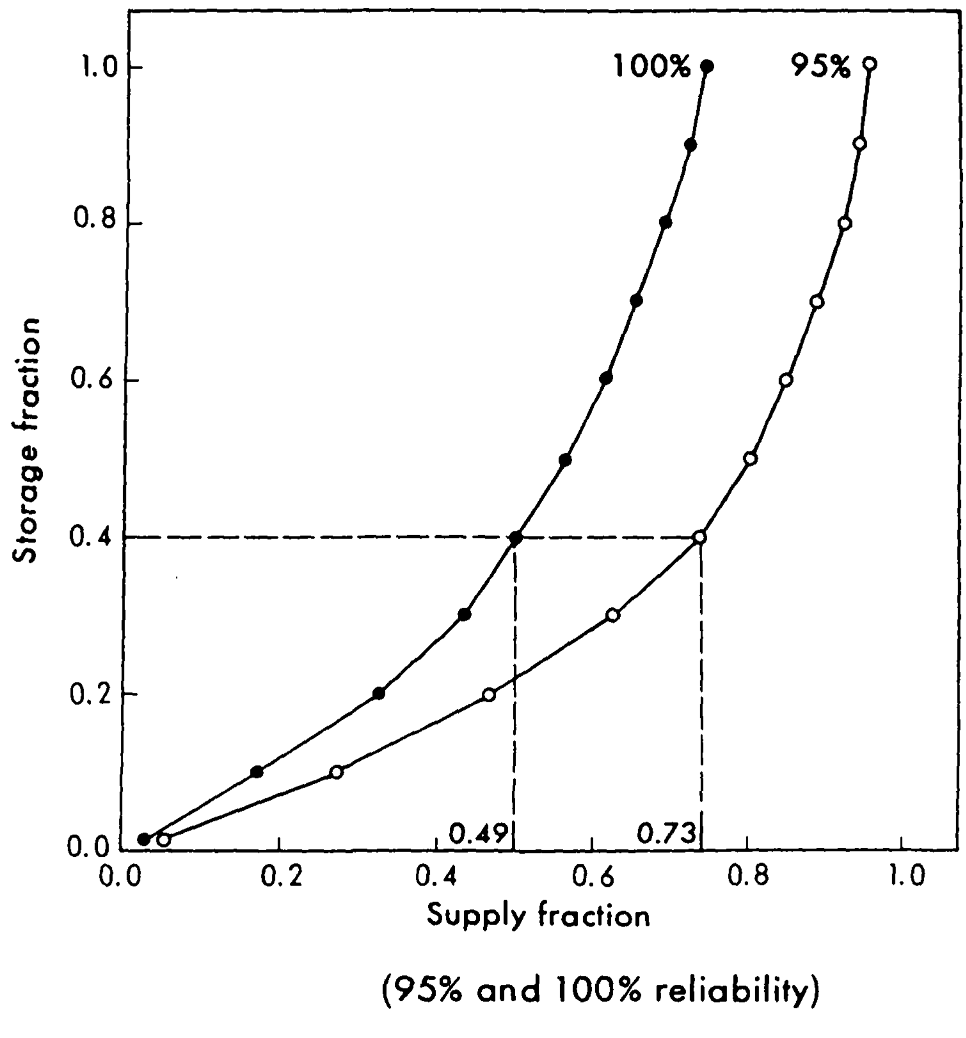


Figure 53. Storage-supply curves for Mahalapye, Botswana

Cost is a key factor, and in East Africa considerable experimentation is currently going on to find the least expensive but technically sound method of building catchment systems. The importance of cost cannot be overemphasized.

(a) Rock Catchments

Reservoirs for rock catchments normally consist of a dam wall behind which an open reservoir stores the rain-water. Generally the surface area of the reservoir will be too large to make covering it economically feasible, despite the considerable evaporation losses which may be expected. In some cases it may be worth investigating the use of cetyl alcohol or other evaporation suppressants for covering the reservoirs. The dam walls are normally constructed of massive concrete, but recent experiments at Mutomo in Kenya (Nissen-Petersen, 1985) have found that a series of buttressed, arched dam walls do the job just as well and require far less material. In some instances tanks have been constructed for storage of rain-water at small rock catchments.

(b) Ground Catchments

Due to the fact that the catchment apron is at ground level, the storage reservoir always consists of a sub-surface tank. Consequently, some method of extracting the water is required, usually either a rope and bucket or some form of pump. The construction of a sub-surface tank requires initial excavation and is best built in consolidated soil.

The low-cost and successful methods of sub-surface tank construction observed in both Kenya and Botswana utilize either butyl rubber or ferro-cement to line an excavated pit. In Botswana a 700 $m^3$ excavated butyl rubber-lined tank used for irrigation was observed at the Forestry Brigade in Serowe. It was still functioning in 1983 after seven years of operation, although it required cleaning. The lining of excavated pits in consolidated soils with butyl rubber is one of the simplest and cheapest methods of ground tank construction, and this approach has been recommended for application in Africa by Bateman (1971).

A more widely used method, however, is the lining of ground catchment tanks with ferro-cement. In Botswana more than 400 tanks of this type have already been constructed and several hundred more are planned. These tanks have been constructed under the Ministry of Agriculture's Arable Lands Development Programme (ALDEP). A detailed description of their construction is given by Whiteside (1982) in a leaflet produced for showing local builders how to construct the tanks. Basically, the method involves lining a cylindrical pit with chicken wire and plastering this with three layers of mortar. The design also includes a concrete base and brick-lined corrugated iron cover (figure 54). The tanks have been successfully constructed in sizes between 5 to 30 $m^3$. The Botswana Technology Centre is presently experimenting with tanks of up to 60 $m^3$ for roof catchment.

This tank design was developed for the collection of rain-water from traditional threshing floors. These plastered mud floors are normally up to 150 $m^2$ in area and are found at most homesteads in the "lands" areas where crops are grown. The construction of permanent cement catchment aprons is preferable in terms of the quantity and quality of water which may be

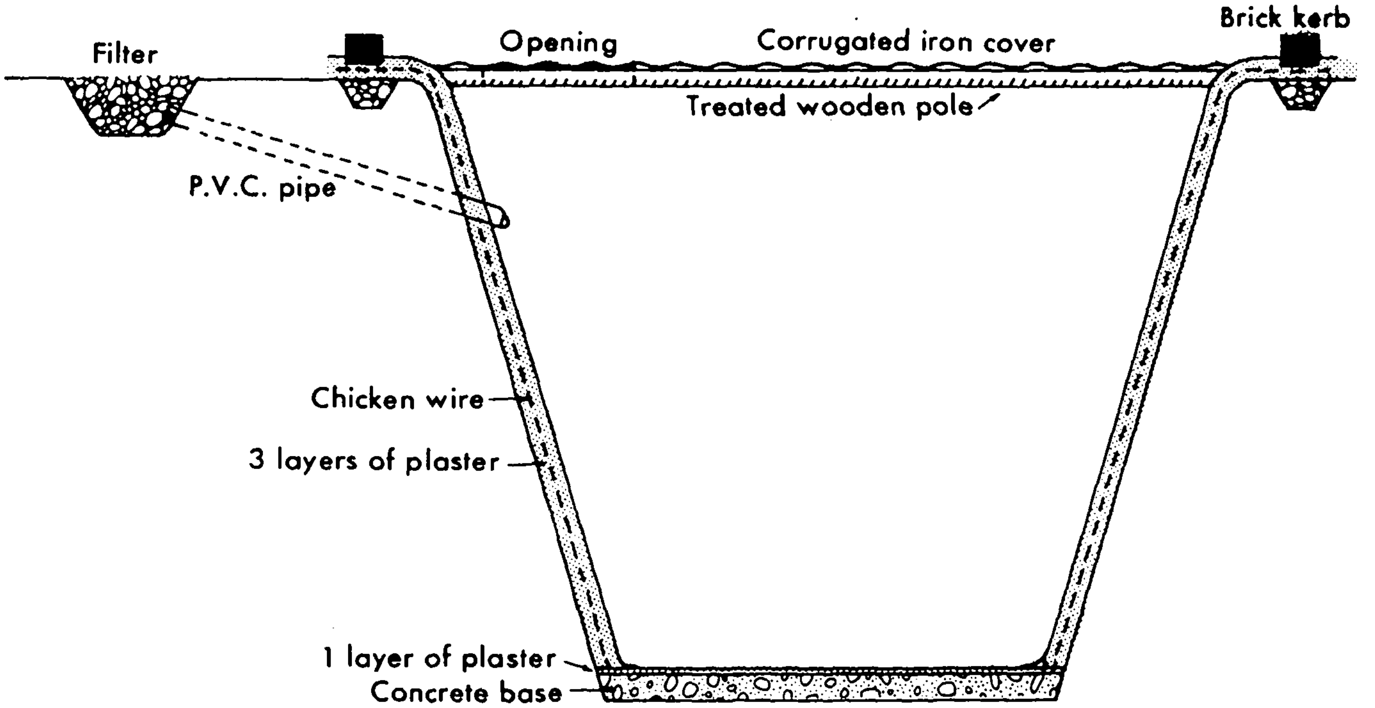


Figure 54. Plastered tank (cross section)

collected, but adds considerably to the cost of the systems. The cost of a 15 $m^3$ tank is currently around $US350 or $US500 if the cost of a 150 $m^2$ cemented catchment area is included.

No pump is included in the design of these tanks. This is to help reduce costs; water is extracted using a rope and bucket. A number of workers have expressed concern about the quality of water from these tanks (Classen, 1980; Maikano and Nyberg, 1981; Whiteside, 1982). Bacteriological analysis of water from these tanks by Gould (1984) revealed faecal coliform counts of between 60 to 1,000 per 100 ml samples. That finding reinforces a suggestion by Whiteside (1982) that water from the tanks should be boiled before drinking. However, few tank owners have taken this advice partly due to lack of firewood and the inconvenience of boiling the water before drinking.

(c) Roof catchment tanks

In contrast to ground and rock catchment systems where storage reservoirs always have to be constructed on site, for roof tanks the option of purchasing a ready-made factory built tank exists.

(i) Factory built tanks

Probably the majority of roof catchment tanks currently used in Africa were constructed in a factory and transported to the site. Although the most common type of catchment tank is the 200 litre oil drum, those are too small to provide for anything more than a few days' storage. The most usual large catchment tanks are factory built corrugated iron tanks, but these are seldom larger than 10 $m^3$. Although these tanks are frequently criticized when comparisons with other tank designs are made, they do offer certain advantages as well as disadvantages. The main disadvantage with regard to corrugated iron tanks is that either the tanks themselves or the steel from which they are produced is imported; therefore the direct installation of the tanks represents a capital intensive technological solution which drains developing countries of previous foreign exchange reserves. The relatively short life expectancy of these tanks is another disadvantage often cited in the literature. Watt (1978) suggests most tanks last for five to ten years.

Galvanized tanks offer certain distinct advantages over other types of roof tanks. The most obvious of these is the convenience of installation. Although the transportation of the galvanized tanks does add to their costs, in Kenya tanks can be delivered to any railway station in the country for as little as Ksh 75 ($US5.00).[1/] The cost of galvanized tanks is not as great as some writers imply (especially for larger tanks). In Botswana a 9 $m^3$ tank sells for P360 ($US250); in Kenya, the price in Nairobi or Mombasa would be $US216. The relatively short life expectancy, especially in coastal areas, due to salt in the air, does reduce the economic feasibility of galvanized tanks in relation to ones made of cement. Although the life span of a galvanized tank depends on the degree of preventive maintenance adopted, such as painting and cleaning, the gauge and quality of metal used to construct the tanks also determines their life span. It seems clear from the fact that many older galvanized tanks installed as early as the 1950s up to the 1970s and 1980s are already leaking, shows that the quality of the tanks being produced

1/$US1.00 = Ksh14.41 (1984 period average).

by manufactures in Kenya and South Africa (most of Botswana's tanks are imported from there) has deteriorated.

One of the greatest advantages of galvanized iron roof tanks over other forms of roof tank, particularly the excavated variety, is the high bacteriological quality of the water stored in them. Figure 55 presents a generalized comparison of the bacteriological rain-water quality for a variety of catchment tanks.

(ii) Roof tank constructed on site

Standard engineering wisdom normally results in considerable over-design of structures to minimize the risk of failure and avoid potentially dangerous disasters. However, when small-scale roof catchment tanks are constructed in that way, the result is very expensive tanks which would be extremely unlikely to cause any serious damage even in the highly unlikely event that they did fail. For this reason considerable time and effort has been invested into the development of much lower-cost tank designs. Although these do not generally adhere to the stringent standards normally applied by civil engineers to such structures, they are nevertheless more than adequate for the job for which they are required. An accurate estimate of the likely life span of some of the designs is not yet possible since they have been developed comparatively recently. In general, however, they have been designed with life spans of at least 20 years, which is more cost effective than the widely-used galvanized tanks, with generally a much shorter life span. Initial indications are that, if properly constructed, many of these low-cost designs are providing the durability hoped for by their designers.

In south-east Asia, one of the successful designs in use particularly in Thailand and Indonesia (Latham, 1984) is the bamboo-reinforced tank. In Africa the absence of bamboo in most areas has lead to designs based on ferro-cement, cement blocks and the use of basket-work frames. Much of the research and development of innovative roof catchment designs has gone on in Kenya. This is partly due to the fact that considerable interest has been generated regarding rain-water catchment technologies by various agencies working within the water sector. In particular, UNICEF, German Technical Aid, the African Medical Research Foundation (AMREF), the Danish International Development Agency (DANIDA), the Catholic Church and the Government of Kenya through its Soil and Water Conservation Projects have all made considerable constributions. Among the dozens of designs which have been developed, four stand out as having been successful both in terms of cost effectiveness and operation. These include cement jar tanks, ghala baskets, concrete ring tanks and ferro-cement tanks.

Cement jar tanks. These are constructed using a hessian or cloth bag mould, which is placed on a pre-cast concrete foundation slab, filled with sawdust, grass, sand or any other appropriate filler and then plastered with mortar (1:3 cement:sand ratio). Once this has set, the filler and mould can be removed. A slab should be cast to act as a cover for the tank and cured for several days. These tanks have been constructed by the hundreds in Kitui district with the support of the Catholic Church and other development agencies. Cement jar tanks can be built up to 10 $m^3$ according to Byrne (1983) but if they are larger than 3 or 4 $m^3$ they must be reinforced with

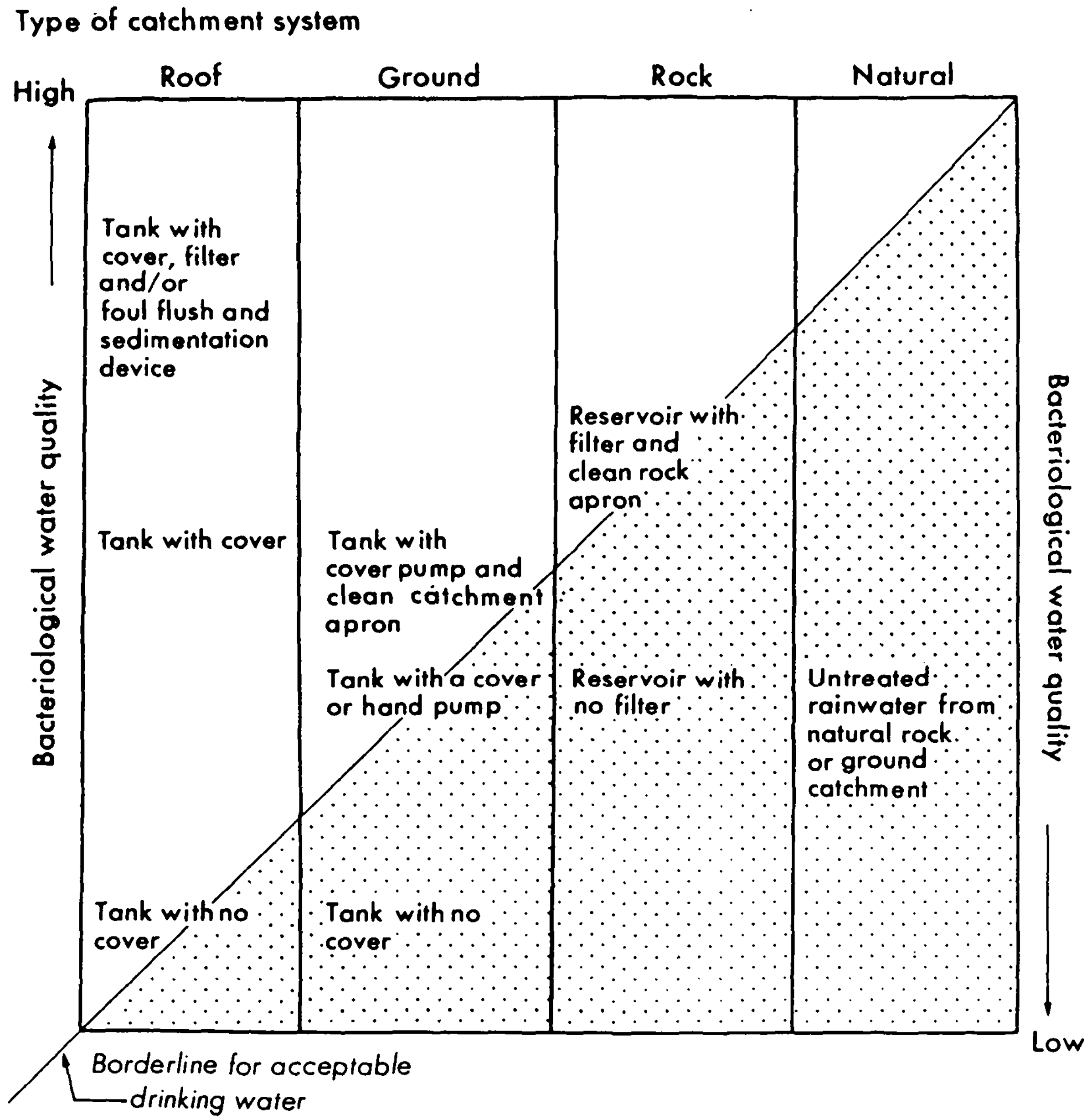


Figure 55. Water quality comparison for different types of rain-water catchment tanks

chicken wire or fencing wire. More detailed descriptions of their construction are given by Nissen-Peterson (1982), Byrne (1983) and McPherson and others (1984).

Ghala basket tanks. More than a thousand of these tanks have been constructed by community groups alone, working under the initial guidance of UNICEF. The design involves applying mortar to the inside and outside of a basket-work frame. Tanks up to 6 $m^3$ can be easily constructed employing only semi-skilled labourers. It is essential that enough cement is used and that the outside as well as the inside of the tank are properly plastered. In North Kitui, for example, some poorly constructed tanks have suffered severe leakage problems. In contrast the tanks built by UNICEF in Karai have performed very well. A detailed description of the materials required and the construction technique is given by Nissen-Peterson (1982) and McPherson and others (1984).

Concrete ring tanks. These are a relatively new type of tank. In Machakos district 350 were built in the space of only 12 months by communities directed by the small local Catholic diocese development office. The rapid acceptance and diffusion of the tanks partly reflects the ease with which they can be constructed as well as their low cost. A 4 $m^3$ tank costs around Ksh 1,400 (US$100) while a 13 $m^3$ tank (the largest so far constructed) would cost Ksh 5,000 (US$333).

The construction of these tanks is accomplished by two concentric corrugated iron ring moulds made by simply bolting curved segments together. The larger mould has a diameter of 10 cm to 20 cm more than the smaller one so that when the two are centred on top of a pre-cast concrete base there is a space into which the concrete is poured. This design is particularly suitable for areas where aggregate is locally available and can be collected and carried to the site by self-help labour. When the first ring of concrete has set, the corrugated iron moulds are removed and placed on top of the previously completed concrete ring. This process is repeated until the required number of rings (usually 2, 3 or 4) have been completed. The tank is plastered inside and out and a ferro-cement cover made for the tank.

Ferro-cement tanks. The advantage of this technology over the three preceeding designs is that extremely large tanks can be built using the ferro-cement technique. According to Watt (1978), it is possible to construct surface ferro-cement tanks with volumes of 400 $m^3$. In Kenya tanks with volumes of up to 129 $m^3$ have been built at Mutomo. For smaller tanks a single cylindrical corrugated iron mould is used. This is normally transported in four segments to the site and bolted together. Chicken wire is coiled around the mould and loops of fencing wire wrapped around this to act as reinforcement. Mortar is plastered on the outside of the mould and when it has finally set, the mould is unbolted and removed. Additional mortar is then plastered on the inside of the tank walls and the base. A highly detailed step-by-step account of this procedure is given by Watt (1978). For larger tanks a movable mould can be used as this allows small portions of the tank wall to be constructed at one time and also avoids the high costs of a very large mould.

Other tank designs recently developed in Kenya which deserve mention, are two varieties of ferro-cement tanks which are built using a weldmesh framework. The first of these is a design developed by a commercial enterprise called "Ferrocraft" in Kilifi. The technique consists of making a cylindrical frame of weldmesh and wrapping it with two layers of chicken wire before applying mortar to the inside and outside of the framework. More than a hundred 6 $m^3$ tanks have been produced in this way and although technically the tanks are very good and extremely durable, they are more expensive than the other designs discussed, selling for around Ksh 5,000 ($US357) each, including transport to the site and a two-year guarantee.

The second ferro-cement weldmesh design is currently being developed by the African Medical Research Foundation (AMREF). This design involves the use of papyrus mat shuttering which is placed on the inside of the weldmesh framework before it is plastered. When the mortar has set, the shuttering is removed. Preliminary results suggest that this is an inexpensive and convenient method.

Finally, Nissen-Petersen (1982) in a recent book on rain catchment and rural water supply in Africa, describes a concrete block tank with a corrugated iron roof which can be built relatively cheaply if the blocks are made on site using community labour.

## 4. Cost comparison

Table 68 shows the cost of a number of different types of roof catchment tanks in Kenya and Botswana. A number of generalizations can be made from these. First, the smaller tanks tend to have higher costs per unit volume. Ironically most poor people buy these because they cannot afford the much larger but more expensive tanks that they really require. Second, it can be seen that although ferro-cement and concrete ring tanks are among the cheapest, they are not significantly cheaper than corrugated iron tanks. Although the potential durability of the ferro-cement tanks is greater than the corrugated iron, this is only the case where ferro-cement tanks are properly constructed and maintained. Where good workmanship cannot be guaranteed, it may be cheaper in the long run to install corrugated iron tanks. In coastal areas, however, due to the rapid rusting which is caused by the salty sea air, ferro-cement and concrete ring tanks are much superior to corrugated iron tanks.

## 5. Experience with rain-water catchment

Some broad generalizations can be made with respect to experience with rain-water catchments in Kenya and Botswana. In both Kenya and Botswana rain-water catchment has been applied mainly in the arid and semi-arid areas where there is an urgent need for water, and surface water and ground water are either scarce or non-existent. An exception to this is in western Kenya where some small individual roof catchments systems are in operation. These however employ the simplest of storage tanks - oil drums or corrugated iron tanks. When questioned during the course of this study, people said they like the taste of rain water. The only exception was found in Botswana, with rain water collected from thatched roofs. This water was not drunk, but was used for washing and other domestic purposes.

Table 68. Cost comparison of different types of catchment tanks in Kenya and Botswana

| Type of Tank | Volume ($m^3$) | Mean Cost ($\$US/m^3$)[a] | Comments |
|---|---|---|---|
| Galvanized oil Drum (Kenya) | 0.2 | 100 | This is the most type of storage tank used. Although cheap, it is too small for most purposes. |
| Galvanized oil drum (Botswana) | 0.2 | 112.5-225 | |
| Corrugated iron (Kenya) | 1<br>5<br>10 | 60<br>26<br>24 | Must be transported to site. Not very durable. Rusts easily, especially in marine environment. |
| Corrugated iron (Botswana) | 2.25<br>4.5<br>9 | 50<br>35<br>30 | |
| Brick/cement (Kenya) | 1-1,000 | 40-60 | This cost assumes a standard engineering design. |
| Ghala basket (Kenya) | 1-8 | 17-40 | 2,000-3,000 have already been constructed in Kenya with varying degrees of success. |
| Cement jars (Kenya) | 1-10 | 33-50 | Larger jars require wire reinforcement. |
| Ferro-cement (Kenya) | 1-200 | 13-26 | This new rapidly expanding technology has the advantage of producing relatively large tanks. |
| Ferro-cement (Botswana) | 20 | 40 | |
| Concrete ring (Kenya) | 1-25 | 23 | These tanks are simpler to build than ferro-cement. |
| Sub-surface Ferro-cement (Botswana) | 20 | 20 | 500 have already been built in Botswana. Although these tanks are cheap, problems of water quality exist. |

Note: These estimates are based on information from projects visited in Kenya in May and June 1984, and in Botswana in 1983.

[a] $US1.00 = Pula 1.89 (1985 period average).

Bacteriological analysis of ground catchment tank water in Botswana showed in the majority of cases that it had unacceptably high levels of faecal coliforms. Faecal coliform counts in eight catchment tanks ranged from 6 to 1,000. Most tanks were above 150. In contrast, analysis of water quality in 13 roof catchment tanks revealed zero faecal and total coliform counts, indicating that this water presented no health risks.

Some problems were noted with the application of rain-water catchment systems in both countries. These tended to be technical due to a poor understanding of what was involved in the design and construction of rain-water catchments. The main problems identified were:

(a) The storage tanks were too small. This was usually because the householder or project organizer did not know how to estimate accurately the storage needs. In Kenya, for example, the Ghala baskets were often much too small. To assure an adequate supply, several baskets were needed.

(b) Tanks leaked or did not hold water. There were several reasons for this. A common fault was that the ferro-cement tanks were not properly cured. Forro-cement tanks need to be kept moist for several days if they are to cure correctly and retain water. In other cases the cement mixtures were not correct and leakage occurred. Some breakage was also noted in ferro-cement tanks built at a central location and transported to the site.

(c) Some tanks were not properly covered. A good cover is essential to reduce evaporation and to protect the water from contamination.

## 6. Advantages and disadvantages of rain-water catchment

Rainwater catchment has a number of distinct advantages which in some situations make it a more acceptable technology than other possible sources.

The advantages can be summarized as follows:

(a) Rain water is clean and free of disease-causing pathogens. As long as the tank is covered, roof catchment systems provide a source of safe water. If bare ground is used as the catchment apron, ground-water catchment systems are more likely to yield contaminated water, as in the case with the ALDEP ground catchment tanks in Botswana.

(b) With roof catchment systems, the water is available at the home. It can even be piped directly into the house. In western Kenya where protected springs are being developed as a source of water, the springs are located at the bottom of deep valleys and the householder must carry the water up several hundred metres along a steep slope. This is much more inconvenient than a roof tank beside the house. Ground catchment schemes usually serve a number of families and some walking is necessary to collect water.

(c) With roof catchment, the householder owns the system. There are tremedous advantages to this. The householder is much more likely to look after the tank and maintain it if it belongs to him.

(d) Operation and maintenance costs are low with roof catchment schemes and usually the owner can do all the work himself. This does away with the need for a government maintenance programme and all the costs associated with such a service. In both ground-water projects and gravity-water systems, experience in Africa has shown that some form of a government central maintenance programme is usually necessary.

(e) The technology is simple and all spare parts or materials necessary to make repairs can be obtained locally. This contrasts with handpump well programmes. In Kenya, for example, there are no handpumps made locally except on an experimental basis. Consequently, getting spares and repairing handpumps is a serious problem and a number of handpump well programmes have failed because the handpumps broke down and were never repaired A case in point is the handpump well programme in the Kwale area along the Mombassa coast. Those handpumps worked for less than a year and none are now operating. Gravity-water systems can also break down; and in Kenya there are examples of schemes which no longer function because of burst pipes or poorly designed and built systems.

There are several disadvantages to rain-water catchment systems. The prime disadvantage is cost. Storage tanks, as we have seen, are expensive to build, so the initial capital outlay is large. This is the reason why so much experimentation is taking place in East Africa to develop the most inexpensive and suitable type of storage tank. Besides the storage tank, there may be other costs depending on whether the system is a ground, roof or rock catchment. A roof with adequate guttering may have to be built because the existing roof is either thatched, too small to provide an adequate supply or has no guttering. In ground catchment systems an apron may have to be constructed of concrete or plastic and in rock catchment schemes a pump may be necessary.

Another disadvantage with rock and ground catchment schemes is that water may require some form of treatment before it can be safely drunk.

## 7. Conclusions

In Kenya and Botswana rain-water catchment is mainly practised in the arid and semi-arid areas and it is still regarded as a technology to be utilized if water cannot be obtained in other ways. This is unfortunate, as rain water, because of its convenience and other advantages, offers great promise for humid areas as well.

Significantly, in both Kenya and Botswana the major assistance agencies in the water sector and all the really large projects are exploiting ground or surface-water sources. Rain-water catchment is the poor relation, and existing schemes are largely the domain of non-governmental organizations and are relatively small in scope.

A positive sign, however, is that some of the major rural water supply programmes are starting to include some rain-water catchments as a component. In Kenya, for example, the German Technical Aid Programme is supporting roof catchments in the Lake Kenyatta resettlement project; the European Economic Community is interested in roof catchments in Machakos district and the Finnish assistance organization has investigated the possibility of roof catchments in their extensive rural water supply programme in West Kenya. These are hopeful signs and suggest that in the future rain-water catchments may play a more significant role in supplying desperately needed water.

In the next several decades in the developing world and especially in Africa, we are going to be faced with a dramatic water crisis. In order to meet this, water will have to be provided as cheaply as possible from systems that are going to have to be largely maintained by the users. Central government operation and maintenance programmes have not been a great success in much of East Africa and to expect a change in the future is unrealistic.

In these efforts to provide water, rain-water catchment should not be neglected as it has been in the past. Because of its unique advantages of technical simplicity and convenience, rain-water catchment can make a major contribution to supplying the desperate needs of large numbers of people.

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## C. Thailand: Rain-water tank project of the Population and Community Development Association

by Pairojana Sornjitti*

### 1. Introduction

Thailand has a population of 51 million (1984 estimate) living in a land area of 514,000 km$^2$ (198,000 sq mi). It can be sub-divided into four major regions: the mountainous north; the plateau of the north-east; the central plain that includes the eastern coastal region; and the south, which is formed by the Malayan Peninsula. Population distribution is given in table 69.

Table 69. Thailand: Population by Region, 1983
(thousand)

| | North | North-east | Central | South | Total |
|---|---|---|---|---|---|
| Population | 10,106 | 17,219 | 16,024 | 6,166 | 49,515 |
| Percentage | 20.4 | 34.8 | 32.4 | 12.4 | 100 |

Source: Records Division, Department of Administration, Thailand Ministry of Interior

Over 80 per cent of the population is directly engaged in agriculture, with rice the major crop. These people live in over 51,000 villages, spread throughout Thailand. The remaining population live in the urban areas, defined as 330 communities that have populations greater than 5,000.

Like most developing nations, Thailand faces a series of problems, including population growth, pollution, the accelerating use of natural resources, and the economic and social problems associated with poverty. On the other hand, the economic progress of Thailand has been impressive over the past two decades. However, there are noticeable gaps in per capita incomes across regions and between the urban and rural populations, as indicated in table 70.

A direct result of the poverty situation that plagues all rural areas and pockets of urban areas is a reduced level of health for the people. This results from a combination of an unhealthy environment, caused by improper sanitary practices, personal behaviour, lack of knowledge concerning basic hygiene, limited supplies of clean drinking water and the inaccessibility of proper health facilities. The north-east region of Thailand is the poorest, and therefore, the problems mentioned are more pronounced and severe.

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Table 70 Thailand: Income distribution by region

| | North | North-east | Central | South | Bangkok | Total |
|---|---|---|---|---|---|---|
| | Percentage of national productivity | | | | | |
| 1960 | 15.8 | 17.0 | 29.3 | 14.1 | 23.8 | 100 |
| 1970 | 15.2 | 16.0 | 27.5 | 12.8 | 28.5 | 100 |
| 1979 | 14.9 | 14.7 | 31.2 | 11.8 | 27.4 | 100 |
| | Per capita income in Baht[a] | | | | | |
| 1960 | 1,496 | 1,082 | 2,564 | 2,700 | 5,630 | 2,106 |
| 1970 | 2,699 | 1,822 | 4,662 | 3,858 | 11,234 | 3,849 |
| 1979 | 8,781 | 4,991 | 17,655 | 12,683 | 30,161 | 12,067 |

Source: National Economic and Social Development Board (NESDB).

[a]/$US1.00 = Baht 27 in this report.

Income distributions from 1960 to 1979 show a widening gap between the four regions. This difference is most noticeable in the north-east, where average annual per capita income was only Baht 4,991 ($185) in 1979 as compared to Bangkok, where the average income of Baht 30,161 ($1,117) was six times greater. Over half of all poor people in Thailand live in the north-east. Approximately 45 per cent of the population in rural areas of the north-east are considered to be living in poverty.

The poverty of the north-east is compounded by the inadequate rainfall and dryness in the region. Because of its geographic location and sandy soils, the amount of ground-water storage is limited. Average rainfall in the region from 1978-1982 was only 1,516 mm occurring mainly during a four-month rainy season. The long dry season lasts from September to April, creating shortages of water for drinking and domestic uses. As wells and ponds dry up, villagers often have to travel as far as 5 km to obtain water, which is often unsafe, and the rate of intestinal ailments and diarrhoea is high.

At present, 70 per cent of the people living in Bangkok are provided with government water supplies, and 60 per cent of the people living in other urban areas have access to piped water from government water works. However, people living in the rural areas must rely upon alternative water supply sources, such as:

(a) Shallow wells
(b) Ponds and/or reservoirs
(c) Rain-water catchments
(d) Artesian wells
(e) Rivers, streams, etc.

An estimated 63.7 per cent of the people in the rural areas have adequate access to the above sources of water. In a 1978 World Health Organization (WHO) report, however, it was estimated that only 10 per cent could be considered safe drinking water.

Based upon the seriousness of the drinking water supply problems in Thailand, the Government willingly accepted its role in the United Nations International Drinking Water Supply and Sanitation Decade (1981-1990). The Fifth Five Year Plan of the National Economic and Social Development Board (NESDB) specifically targeted those poverty areas where drinking water supplies are in shortest supply. The plan promoted the use of appropriate technologies, and extended the opportunities for people to help themselves by establishing co-operative groups and revolving funds. The plan also mobilized the joint efforts of the government and non-governmental organization (NGOs). The workplan and budget for the Fifth Plan are in tables 71 and 72, respectively.

Table 71. Provision of clean water supplies in Thailand's Fifth Five-Year Plan

| Target Activity | 1981-2 | 1982-3 | Fiscal Year 1983-4 | 1984-5 | 1985-6 | Total |
|---|---|---|---|---|---|---|
| Total villages served (30 provinces) | 3,000 | 3,000 | 3,000 | 3,000 | 1,683 | 13,683 |
| Village water supply systems | 500 | 500 | 500 | 500 | 500 | 2,500 |
| Rain-water catchment tanks (3 $m^3$) | 3,000 | 3,000 | 3,000 | 3,000 | 1,683 | 13,683 |
| Water jars | 3,000 | 3,000 | 3,000 | 3,000 | 1,683 | 13,683 |

Source: NESDB

Table 72. Budget for clean water supplies in Thailand's Fifth Five-Year Plan

| Target Activity | 1981-2 | 1982-3 | Budget (Millions of Baht) 1983-4 | 1984-5 | 1985-6 | Total |
|---|---|---|---|---|---|---|
| Village water supply systems | 17.50 | 17.50 | 17.50 | 20.00 | 22.50 | 95.00 |
| Rainwater catchment tanks | 10.50 | 10.50 | 10.50 | 12.00 | 7.57 | 51.07 |
| Water jars | 0.75 | 0.75 | 2.40 | 3.00 | 1.68 | 8.58 |
| Other activities | 2.97 | 2.97 | 17.33 | 16.73 | 10.72 | 50.72 |
| Total | 31.72 | 31.72 | 47.73 | 51.73 | 42.47 | 205.37 |

Source: NESDB

Note: The total budget targeted for poverty areas in the Fifth Five-Year Plan is Baht 8,153 million (US$302 million).

## 2. The Population and Community Development Association

The Population and Community Development Association (PDA) is a private non-profit organization founded in 1974 with the objective of co-operating with the Government to promote basic solutions to the development needs of the country. With the approval of the National Family Planning Committee, PDA began implementing family planning and primary health care programmes. The PDA model for family planning delivery services emphasized the development of a grass-roots network of volunteer distributors.

From its recognized success, PDA expanded it activities to include other development projects in 1978. Aiming to improve the quality of life in the rural areas, PDA wanted to provide the opportunity for villagers to co-operate and participate in their own development process. The network of over 16,000 volunteer distributors provided a ready-made link between PDA and the rural areas.

## 3. Rain-water Tank Pilot Project

Through survey data and information provided by the Ministry of Public Health (MOPH), PDA estimates the average water consumption to be 55 liters/person/day, of which 4 are required to meet basic drinking water needs. It is the goal of the Water Decade that all people will have access to clean water for drinking by 1990. By the year 2000, the population will be about 60 million. According to current plans, 8 million will receive a piped water supply and the remaining 52 million will enjoy other sources of clean water. Tables 73 and 74 show the targetted water resources needs and necessary budget to meet this goal.

In 1978, PDA began its own water resources development programme as a supplement to the activities of the Government, with the promotion of shallow wells and latrines. In 1980, these activities were expanded to include rain-water catchment in village ponds, bored and dug wells, hand pumps and rain-water tanks. The latter being in three villages.

The pilot project in which 53 tanks were built, had two major objectives:

(a) To test tanks of varying capacity, utilizing three different types of construction: ferro-cement, bamboo-reinforced concrete and cement rings.

(b) To evaluate community participation in tank construction and to measure acceptability and effectiveness of the revolving fund mechanism for raw material costs.

A system of co-operative work was used for tank construction and PDA acted as adviser and supervisor. In the revolving fund mechanism, the villagers agreed to provide all necessary labour, while PDA provided tools and equipment, a technician and raw materials at cost. Every family that constructed a water tank had to provide one labourer who worked in a group of seven or eight, building one tank for each family in that group until all tanks were completed. One tank can be constructed per day. One or two especially motivated and adept workers were trained to help others in the same village to properly maintain their tanks.

Table 73. Thailand: Water resources and budget needs

| Type | Number | Coverage (million people) | (percentage) | Ten Year Project Budget (million Baht) |
|---|---|---|---|---|
| Public wells | 873,800 | 39.3 | 75.1 | 961 |
| Shallow wells | 10,000 | 2.0 | 3.8 | 600 |
| Rain-water catchment | 474,900 | 2.7 | 5.2 | 1,601 |
| Village water supply | N.A. | 8.3 | 15.9 | 5,766 |
| TOTAL | - | 52.3 | 100.0 | 8,928 |

Table 74. Thailand: Total number of rain-water catchment tanks to be constructed by the year 2,000

| | Total | Number of Villages[a] | Suburban Areas[a] | Cities and Municipalities[a] | Bangkok |
|---|---|---|---|---|---|
| Households (Tanks) | 474,900 | 144,700 | 18,600 | 97,700 | 203,900 |
| Population Served | 2,714,000 | 802,200 | 150,200 | 501,200 | 1,260,400 |

[a] Excluding Bangkok

Notes:

1) These projections assume that water tanks will be built in areas where no other water resources facilities are located.

2) The water tanks will be built using a community-based system under the supervision of government or private agencies.

3) These projections assume that all recipients of water tanks will repay raw material costs into a revolving fund for future tank construction.

Upon completion of the new tank, owners are expected to repay material costs, in one lump sum or on a monthly instalment basis. Most villagers opted for the second method, signing a contract and making an initial payment of the equivalent of $US18.50, followed by monthly payments of $3.70 to $7.40 over 8 to 17 months, with no financing or interest charges. The raw material costs varied from $47 to $113, depending upon the type of tank.

From the pilot project, PDA concluded that:

(a) This is a viable method of providing a clean drinking water supply in rural areas;

(b) The villagers were highly receptive to bamboo-reinforced concrete tanks because of the local availability of bamboo, ease of the construction and reasonable costs (see table 75).

(c) Labour sharing among tank recepients and training of local technicians reduced labour and future maintenance costs. The construction techniques acquired by villagers and the experience gained from working co-operatively were extra benefits.

Table 75. Comparison of costs for various rain-water catchment systems (US dollar equivalents)

| Type of system | Capacity (litres) | Unit Cost ($US) | Cost/$m^3$ ($US) | Labour Costs (Man-days of construction) |
|---|---|---|---|---|
| Small water jar (1 $m^3$ or less) | 40 - 200 | 2 - 10 | 50 | Included in price |
| Giant water jar (2 $m^3$) | 1,400 - 2,000 | 15 - 35 | 12 - 25 | Included in price |
| Metal tank (1.2 $m^3$) | 1,700 | 90 | 50 | Included in price |
| Cement ring tank a/ (2.5 m high, 1.2 m diameter) | 2,400 | 60 | 25 | Not available b/ |
| Ferro-cement tank | 3,400 | 90 | 26 | Approximately 4 days b/c/ |
| Bamboo-reinforced cement tank (3 m high, 1.5 m diameter) | 5,300 | 120 | 23 | 5 to 7 tanks in 10 days d/ |
| (3 m high, 2 m diameter) | 9,400 | 160 | 17 | |

Notes:

a/ Inner diameter 1.12 m.

b/ Construction data for cement ring and ferro-cement tanks are somewhat unreliable as the sample size for these two types of tanks was small.

c/ Calculated using the formula of 4 man-days for technicians with 10 villagers working each day.

d/ Calculated using 12 man-days with 10 villagers working per day to build 5 to 7 tanks. Each household provides 1 labourer/tank/day.

(d) The revolving fund repayment mechanism was acceptable by the villagers to pay for the raw materials. The project was conducted in two phases, with the repayments from tanks built in the first phase funding construction of tanks in the second. This created an incentive for villagers to make monthly payments promptly.

(e) Though villagers were only responsible for repaying the raw material costs, in order that future projects attain financial self-sufficiency, it was decided to reduce costs by: ordering raw materials in larger volumes; including both material and administrative costs in the repayment plan; and including a small interest charge.

The results of the small pilot project were encouraging; all tanks were built according to standard construction techniques, and villagers co-operated enthusiastically in the group setting. Repayments into the revolving fund were made on time, and the project progressed smoothly.

### 4. Tungnam Rain-water Tank Project I, II, III and IV

The successful water tank pilot project led PDA to continue its efforts in water resources development along similar lines. In 1981, the First Rain-water Tank Project (Tungnam I) was implemented, with the following objectives:

(a) To provide a source of sanitary drinking water for rural families of north-east Thailand.

(b) To develop a community-based system for the delivery of that service.

(c) To promote village-level co-operation in development activities.

(d) To create an administrative system for the revolving fund mechanism that could spur village development activities without external financing.

(a) Implementation description

Bamboo-reinforced concrete rain-water catchment tanks with a capacity of 11.3 $m^3$ are built for those households which request them. They are 3.6 m high and have a diameter of 2 m, sufficient in size to supply the water needs for a seven-member household through the eight-month dry season. The tank becomes the property of the household that constructs it and pays for raw material costs. Although PDA considers single household ownership to be preferable, about 20 per cent of the tanks are purchased jointly among two or more families.

Families intending to purchase the tanks provide one labourer each and, grouped into 8 to 15 workers, they build one tank per family. The workers are expected to collect bamboo, prepare the tank foundation and to construct the tank themselves.

The raw material costs were set at Baht 4,000 ($148) per tank for Tungnam I. This was increased to Baht 4,200 ($156) in Tungnam II and to Baht 4,400 ($163) in Tungnam IV. At the completion of each tank, the recipient signed a contract stipulating monthly repayments equal to $7.40 without an interest charge. A down payment of $18.50 was made at the time the contract was signed. Tank recipients could choose to repay in one lump sum.

During construction, PDA selected a village tank technician to receive additional training. He is to help the new tank owners maintain and clean their tanks properly, and to help supervise the monthly repayments to the revolving loan fund. Any follow-up activities sponsored by either PDA or local government officials are to be co-ordinated by the volunteer technician. PDA also establishes a village committee to select future tank recipients and to administer the revolving loan fund.

(b) Work Criteria

The following criteria, incentives and guarantees comprise the modus operandi:

(i) Village selection criteria

Villages are selected for rain-water tank projects on the basis of: lack of available clean waer supplies; a reputation for co-operation and collaboration in past development efforts; involvement in the government development plan; and a high level of family planning acceptance.

(ii) Member recipient selection

Individuals or families are chosen for: their willingness to purchase and construct a water tank for household use; their reputation for involvement in community development activities; their ability to pay for raw material costs to the revolving fund; and their willingness to practise family planning.

(iii) Special incentives and agreements

There are discounts in the repayment schedule if the tank recipient introduces neighbours and friends to family planning.

(iv) Water tank guarantee

A three-year guarantee provides for the free repair of any problems resulting from faulty construction or improper mixing and setting of the cement. If the tank should become inoperable within 15 years of construction, PDA will be responsible for the construction of a new water tank free of charge to the recipient. For the previous two situations, the tank owner must provide all necessary labour. The guarantee does not cover damages caused by natural disasters, such as earthquakes or flooding, or from improper or careless use of the tank.

(c) Implementation locations

At the present time, PDA rain-water tanks have been or are being constructed in 20 districts of four provinces in north-east Thailand. The four provinces are Khon Kaen, Mahasarakham, Buriram and Nakhon Ratchasima. A newly implemented pilot project is introducing the water tank in Kamphaengphet Province, a dry area in the northern region of Thailand. A summary of total costs of the project is presented in table 76.

In addition to the Rain-water Tank Projects, PDA also provides other types of water development technology, including the giant water jar, shallow wells, bore wells and village pond construction and improvement. This variety of options allows the target beneficiaries to select the appropriate resource to meet the needs of their particular situation. In villages with particularly low average income levels, PDA first offers income-generating development projects that will allow the villagers to increase their household income level and to engage in new productive activities. The income acquired from these activities can then be used to purchase one of the available water resource systems.

Table 76. Analysis of total costs for rain-water tank project
(million baht)

| Component | 1st Year | 2nd Year | 3rd Year | 4th Year | Total | Percentage |
|---|---|---|---|---|---|---|
| Raw Materials | 4.0 | 6.7 | 11.3 | 15.8 | 37.9 | 70 |
| Administrative and Operating Costs | 1.2 | 2.0 | 3.4 | 4.8 | 11.4 | 30 |
| Total | 5.2 | 8.7 | 14.7 | 20.6 | 49.3 | 100 |
| Revolving Funds Needed | 4.0 | 4.2 | 6.3 | 6.6 | 21.1 | 42.8 |

Note: The above figures are based upon the following:

(1) Administrative operating costs are proportional to the number of tanks constructed.

(2) The raw material costs charged by the revolving fund were increased due to inflation and increased prices.

(3) The assumption is that these estimated figures reflect the true cost of water tank construction.

The rain-water tank project was selected as the main method for providing clean drinking water supplies owing to the cost effectiveness of water tanks. The Thai-Australia Village Water Supply Project, a study completed in 1984, found water tanks to be an inexpensive way to provide drinking water for household consumption due to the durability and low maintenance costs associated with the tanks. This study found water tanks to be less cost-effective than shallow wells and water jars. However, the jars are too small to accommodate the large household sizes in the north-east and shallow wells are easily contaminated. The water tank was therefore selected as the optimal solution.

(d) Factors leading to project success

(i) Use of an appropriate technology

Small water resources development techniques should be easily understood and accepted. Both the rain-water catchment tank and the giant water jar can be easily constructed by villagers with only a few tools and basic training. Both of these systems can provide the drinking water needs of a family in an easily accessible manner.

(ii) Co-operation of the villagers

By providing frank and honest explanations about the benefits and associated costs of the rain-water tank, villagers were able to understand the desirability of a water tank construction programme. This helped to motivate them to join the project and to work together to ensure its successful completion.

(iii) Individual ownership and group belonging

By sharing in the work experience, villagers gain a sense of pride in their work. In community water resources projects, PDA also encourages group co-operation. In pond construction and improvements, the villagers work together for a common goal, gaining a sense of community possession and spirit.

(iv) Villager acceptance

The raw material costs of the water tank and the giant water jar are lower than the market price. Repayments for these costs are also made in small amounts on a down payment and monthly instalment basis. Understanding this repayment system and the low price of the raw materials, the villagers are willing to accept and support the project.

(v) Reputation of the organization

Most villagers have experience working with outside agencies, whether they are governmental or private. They have also seen agencies and individuals that have taken advantage of them. Therefore, a reputation of honesty and reliability of the organization is essential to spur the co-operation of the villagers. Adequate staff support and rapport are also important, since they work together with the villagers to guarantee project success.

(vi) Co-ordination with other organizations

PDA works to supplement the work of the government. With this intention and attitude, the local government officials are supportive of the project, and can serve as the liaison and co-ordinators between the villagers and PDA.

(vii) Utilizing beneficial traditions and customs

In Thailand, the villagers work together during the harvest season, moving from one field to another, helping their neighbours. The water tank projects utilizes this same group co-operative spirit, for the benefit of the community. This creates an atmosphere of self-help and responsibility among the villagers rather than having them accept a handout.

## 4. Conclusion and suggestions

The success of a small water resources development project is facilitated by the co-operation of the target villagers, who must realize the benefits of such a project for themselves and their community. Understanding this, they are ready and willing to help. The project should offer water systems that are simple, employing a technology that is appropriate to the village environment. The simplicity of the technology will allow the villagers to take part in the actual preparation and construction of the systems, serving as a strong motivating influence. When the villagers work for the success of the project, it becomes their project, and they have a sense of belonging and pride in the results of their efforts.

Additional support from other local agencies is a great asset to the project, and their co-operation should be solicited through an open invitation for approval and co-operation. As the villagers utilize these local resources, their steps toward self-reliance and self-sufficiency will be complemented through their mutual efforts with the local community organizations.

## Appendix: Construction techniques for Thailand's Bamboo-Reinforced Concrete Rain-water Catchment Tank

### 1. Site selection

The water tank should be built on a flat piece of land where the soil has been firmly compacted. The tank must be at least 2 m from any well, latrine or sloping area. If there is a tree root or stump in the area near to the tank construction site, it should be removed and soil should be filled in and firmly compacted.

### 2. Preparation of the foundation

A square hole of 2.5 m on each side and 25 cm in depth should be dug. The edge of the hole must be straight and vertical, making a perfect square. The ground then must be compacted further, with alternating layers of soil and gravel, each 5 cm thick, pounded into the hole. After completing this layering process, water should be poured over the area, and the square should be compacted further to a depth of 3 cm below ground level.

### 3. Preparation of the bamboo frame

Using local bamboo that is at least two years old, the bamboo should be cut and split into strips 2 cm in width with a thickness of 1/2 to 1 cm. The pieces should be smoothed and cut to the following specifications:

13 pieces 7.5 m long for horizontal reinforcement
20 pieces 4.2 m long for vertical support
48 pieces 2.35 m long for the foundation and cover

The bamboo for horizontal reinforcement should be sharpened on both ends to enable the strips to be formed into a circle of circumference 6.66 m by tightly tying the strip with three pieces of wire.

The vertical strips should be flattened by hammering 40 cm in from both ends. This hammering should be done while the bamboo is still fresh. If the bamboo is dry, it should be soaked in water for 2 hours prior to the flattening process. While hammering, cutting of fibres should be avoided, since these are what give the bamboo its strength.

### 4. Bamboo frame

The frame for the foundation is made by tying the 24 bamboo pieces of length 2.35 m together. The 12 pieces of bamboo are laid in a parallel fashion on the ground, with 20 cm between each strip. The remaining strips are then laid perpendicularly on top of the first layer, following the same pattern, but leaving 7.5 cm of an overhang on each strip. On the ground, a circle of diameter 2.12 m should be drawn. The circumference can be divided into 20 equal parts of 33 cm each. The bamboo frame is then placed on the circle and adjusted to be well centred. The vertical bamboo strips are tied to the foundation frame at the points on the circle that have been marked. These vertical strips will be tied together on the top, and the horizontal bamboo circles will be tied to the vertical strips, with 20 cm between the base and the first circle and 20 cm between all other horizontal circles.

The remaining 22 pieces will be tied up the entire vertical frame. The top will be cut into a circular shape of 2.16 m and shaped into a manhole of 50 cm square. A bamboo frame for the manhole cover can be made with the remaining bamboo strips.

5. Tank base

A wooden frame of 2.5 m square is placed in the foundation hole and main level, rising 15 cm above ground level. The concrete mixture is prepared in a ratio of 1:2:4 (1 1/2 bags of cement, 17 pails of sand, 30 pails of crushed rock and 6 pails of water). The sand is put into the mixing pan first, spread evenly. Then cement is added, mixing thoroughly. The colour should be uniform. The crushed rocks should be placed on top and then water added, waiting ten minutes. Using hoes (four labourers with two hoes) the cement is mixed in three rounds. More water can be added, only if necessary. If the sand and rock are wet before adding the water, less water should be used. The slump of the mixture should not be greater than 10 cm.

Using shovels, the mixture should be put into pails to pour into the foundation frame while a worker kneads the mixture with his feet as it is poured into the frame. A shovel should not be used to put the mixture directly into the frame, because this will cause the cement to set improperly in the form. The bamboo frame should then be placed on the centre of the cement mixture, pushing it into the wet cement. The surface level should be adjusted and the drainage pipe placed into the middle of one side. The plug end of the pipe should stick out of the base 2 cm below the top, with the inner end of the pipe 1 cm lower than the level of the cement. Trowels can be used to dig out the cement before putting in the drainage pipe, and a hammer can adjust the drainage pipe level, putting paper into the drain pipe to keep it clear of cement. Then dry cement can be spread over the surface of the base and water sprinkled on this, smoothing the surface, until it is shiny. The surface should be roughed up with a trowel where the tank wall will be helping to form a seal when the wall is poured.

6. Tank wall

The base should be cleaned with water after it has set, letting the water saturate the base for two hours. In the meantime, oil should be applied to the metal forms for the walls before assembling them into the base.

The thickness of the inner and outer walls of the metal form should be measured, making sure the bamboo frame is equidistant between the two. Paper cement bags can be used to line the interior wall of the metal forms to cover the seams. Water should be poured over the seams to clean them.

The ratio of 1:2:3 (2 bags of cements, 20 pails of sand, 30 pails of crushed rock and 8 pails of water) can be used for the cement mixture for each mixing pan.

Two pails of cement and water can be mixed and applied to the base where the walls will be poured to help create a more permanent seal. When the cement is poured into the metal forms, it should be performed in an orderly fashion. The cement should be applied to maintain an even level around the entire circle, and someone should continue to tamp the cement, adjusting the bamboo frame throughout the pouring process.

After the first ring has been finished, the second inner ring may be fixed to the first, tying the fourth bamboo circle 20 cm above the third. The outer ring is then attached and pouring continues. This process will continue for the next four rings, using the same technique. All pouring must be completed on the same day, because a halt in the pouring process may create a seam in the wall. If pouring is interrupted for any length of time, a water-cement mixture must be applied before the pouring can continue.

After the pouring process has been completed, the top of the wall can be prepared by covering the frame with four pairs of banana leaves.

A banana stalk can be used to make a groove for the overflow pipe. The inner and outer walls of the metal form should be cleaned of any spilled concrete.

### 7. Metal forms

After the cement has set for 24 hours the inner wall of the metal form can be removed from the top down. The outer mould forms should not be loosened or removed until the inner wall has been removed. Then, the outer forms can be removed from the top down. Any shaking may damage the tank wall. The metal forms should be cleaned and oil applied thoroughly, covering the entire surface.

### 8. The surfaces of the wall

The inner and outer wall should be cleaned using water, checking for cracks and making any necessary repairs. After this step is finished, a water-cement mixture can be applied to the outer wall and then using a trowel, a cement-sand mixture (1:2) can be added to decorate the outer surface. This process is completed twice, with the second layer being applied more gently than the first.

On the inner wall, a water-cement mixture can be applied, followed by a coat of two layers of a cement-sand mixture (1:3). A small triangular-shaped rim can be added around the inner and outer walls, then covered with cement and sand. The faucent attachment should be cleaned and the cement surface made rough in order to attach the faucet reinforcement cover.

### 9. Water tank ceiling

The banana leaves should be removed from the top of the wall and excess bamboo that is protruding from the top of the wall should be cut. Four beams are placed on top of the wall, and the wooden form is put on top of the beams. The level of the ceiling mould is adjusted to be parallel to the ground. The metal form is attached and the bamboo frame put into the formwork.

After cleaning the edge of the wall that will attach to the ceiling, water should be applied thoroughly and then cement added. The cement for the ceiling should be mixed in a ratio of 1:2:3 (1 1/2 bags of cement, 16 pails of sand, 24 pails of crushed rock and 6 pails of water). While pouring the cement into the ceiling mould, the bamboo is shaken to assure that there is no space between the concrete and the frame. The bamboo is adjusted to be in the middle of the concrete. A manhole, a 45 cm square 20 cm from the outer wall, is added to facilitate tank cleaning and maintenance. The size of the manhole cover is 50 cm square and 2 to 3 cm thick.

### 10. Removal of the ceiling frame

After drying for 36 hours, the beams supporting the ceiling form can be removed. The overflow pipe is attached and the holes where the beams had been are sealed shut with bricks and cement. The plug is placed into the drain pipe, the faucet spout added, the by-pass pipe attached and the manhole closed.

More detailed information and an owner's manual can be obtained from the Tungnam Project, Population and Community Development Association, 8 Soi 12 Sukhumvit, Bangkok, 10110 Thailand.

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V. EXPERIENCES WITH WATER REUSE AND WEATHER MODIFICATION

## A. Egypt: Reuse of drainage water in irrigation

by Samia El-Gindy*

### Introduction

Direct reuse of drainage water began early in Egypt by routing all main irrigation drains of Upper Egypt back into the Nile to be mixed with the river water and rediverted into Middle and Lower Egypt. The reused drainage water of Upper Egypt amounts to about 2.7 billion $m^3$ annually. Officially an estimated amount of 2.6 billion $m^3$ is reused in the Delta by pumping to the nearest irrigation canal or to one of the Nile branches. In addition, an unknown amount is unofficially used directly from drains by farmers, either for irrigation or to supplement fresh water during periods of peak demand. In 1975, the reuse of drainage water became an official strategy of the Ministry of Irrigation in order to supply part of the envisaged extension of the agricultural acreage with water.

To assess the quantity and quality of drainage water that can be used for irrigation purposes and allocate different sources of this water to the appropriate use, the Drainage Research Institute (DRI) has worked since 1977 on a programme to collect the maximum amount of data in the shortest period of time. A network of about 95 measuring locations, 57 of which are pumping stations in the Nile Delta and Fayoum, was set up and regular measurements of the quantity and quality of drainage water started in 1980.

Future changes in both quantity and quality of drainage water not foreseen under the present conditions of irrigation practice, cropping pattern and so on, can seriously affect the amount of drainage water suitable for reuse. For this reason, the Ministry of Irrigation of Egypt and the Ministry of Foreign Affairs of the Netherlands decided, within the framework of a joint programme of technical co-operation, to fund a "Re-use of Drainage Water Project". The objectives are:

(i) To assess the quantity and quality of the water drained off and not being used for irrigation at present;

(ii) To predict the time trends of the parameters influenced by sub-surface drainage, increases in cropping intensity and improved water management;

(iii) To monitor the change in these parameters over time;

(iv) To collect data to produce on overall water and salt balance for the Delta;

(v) To indicate where and how drainage water can be reused;

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(vi) To evaluate the effect of reuse of drainage water on crop production.

This paper presents the data on water quantity and quality and studies of three projects using drainage water to reclaim new lands in the Delta and Fayoum.

## A. The measurement programme

In 1979, DRI started collecting data on the quantity and quality of drainage water. The 95 measuring points chosen are distributed as follows:

| Region | Area million feddans | Measuring points location | | | |
|---|---|---|---|---|---|
| | | Total | Pumping stations | Open drains | Outfalls |
| Eastern Delta | 1.33 | 28 | 17 | 9 | 2 |
| Middle Delta | 1.55 | 27 | 20 | 3 | 4 |
| Western Delta | 0.88 | 23 | 19 | 3 | 1 |
| El Fayoum | 0.32 | 17 | 1 | 13 | 3 |

Note: 1.0 feddan = 0.42 hectare (ha)

Discharge measurements at predetermined sections along the main drains are carried out every two weeks by the velocity-area method. From 1979 to 1982, the flow velocity was measured with floats as well as pendulums. Both float and pendulum methods have a number of drawbacks which affected their accuracy. However, they are more practical to use than the current meter method, requiring less manpower and time. At present, the stage-discharge relationships through the current meter (rating curve) for each cross section are being established by DRI. Moreover, the installation of automatic continuous recorders of the water levels have been installed at all measurement points. Thus, accurate estimates of the drainage water discharges can be made.

To improve the accuracy of discharge measurements at the pumping stations, three steps are carried out:

(1) Installation of time counters for recording the number of operating hours of each pumping unit.

(2) Calibration of each pumping station to determine the actual capacity of each unit for various head conditions.

(3) Installation of automatic water level recorders for continuous reading of the water levels at both suction and discharge ends of the stations.

Drainage water discharges at the outfalls of drains are affected by the backwaters caused by levels of the lakes. In such cases the dischage-stage relationships are not accurate, and cannot be used for estimating discharges. It is planned, therefore, to install daily velocity recorders at the outfalls to enable computation of an accurate estimate of discharges.

For water quality measurements, sub-samples are collected from the delivery side of each operating pumping unit and combined to make a composite sample for each of the pumping stations. In sampling and open drains, five equally spaced sub-samples are collected between the left and right bank at about 1 m below the surface to make a composite sample. Analysis is performed at the DRI laboratory and includes measurements of electric conductivity, pH and the soluble cations and anions.

### B. Drainage water quantity and quality data

#### 1. Quantity

The total amount of drainage water reused for irrigation in Egypt is estimated at 2.615 X $10^6$ $m^3$ (see table 77). This excludes amounts directly utilized by individual farmers from drains, for which totals are not known. Most of the water is discharged into the Mediterranean directly by gravity or through a series of pumping stations that lift drainage water from the main drains. The volume of this water is estimated at about 13.881 X $10^6$ $m^3$ per year (see table 78).

#### 2. Quality

The average of the minimum and maximum values for total salinity and adjusted Sodium Absorption Ratios (SAR) were calculated for the period 1978-1983 for the East, Middle, and West Delta, and El-Fayoum regions.

The data indicate the following:

(a) About 80 per cent of discharges into the sea had a salinity below 2,000 ppm.

(b) The salinity for all drainage water was in the range of 400 to 5,000 ppm. The average salinity was between 1,300 - 1,500 ppm. Considering that the original salinity of irrigation feed water is around 300 ppm, a salinity for the drainage water of around 800 ppm would have been expected. Therefore, the over-all salinity average of the drainage water was quite high.

(c) Salinity differences were found among the various parts of the Delta, with higher spot concentrations in the western part and locally in the eastern part, while the lowest figures were encountered in the central part.

(d) The salinities in general rose from the south to the north according to soil texture and salinity.

(e) The quality of the water in the El-Fayoum area is relatively good; the salinity of the water from the drains discharging into Lake Karoun, does not exceed a salinity of 1,500 ppm.

Table 77. Reused drainage water in the Nile Delta region

| Region | Drainage or pump station | Source of drainage water | Outfall | Quantity ($10^6 m^3$/year) |
|---|---|---|---|---|
| Eastern Delta | El-Wady pump station | Main Kalubia drain | Eastern Valley Canal | 457 |
| | Hanut pump station | Southern Bahr Saft drain | Hanut Canal | 245 |
| | Upper Serw pump station | Upper Serw drain | Domietta Branch | 141 |
| | Bahr El-Bakr pump station | Bahr El-Bakr drain | Battickh Canal | 35 |
| Middle Delta | Tela drain | Tela drain | Rosetta Branch | 177 |
| | Sebl drain | Sebl drain | Rosetta Branch | 177 |
| | Eastern Munofia pump station | El-Kadnien drain | Abbasy Rigah | 176 |
| | Mahalet Ruh pump station | Mahalet Ruh drain | Miet Yazied Canal | 78 |
| | Upper No. 1 pump station | Upper No. 1 drain | Domietta Branch | 112 |
| | Hamul pump station | El-Gharbia main drain | Bahr Tiera Canal | 265 |
| Western Delta | Etay El-Baroud station | Etay El-Baroud drain | Eastern Kandek Canal | 40 |
| | Western Khundek pump station | Western Khundek drain | Abu Diab Canal | |
| | Delingat pump station | Delingat drain | Ferhash and Hagez Canals | 199 |
| | Edko pump station | Edko drain | Mahmoudia Canal | 356 |
| | | | Total | 2,615 |

Table 78. Discharges of the main drains of the Nile Delta and for El-Fayoum at the outfalls (1972-1981)

| Region | Drainage Water Destination | Drainage Quantity ($10^6 m^3$/year) |
|---|---|---|
| 1. Eastern Delta | | |
| a. Bahr El-Bakr drain | Manzala Lake | 1,563.0 |
| b. Bahr Hadous drain | Manzala Lake | 2,637.5 |
| c. Lower Serw pump station | Manzala Lake | 574.2 |
| d. Materia pump staton | Manzala Lake | 154.4 |
| e. Farasquor pump station | Manzala Lake | 240.4 |
| Total | | 5,169.5 |
| 2. Middle Delta | | |
| a. Lower No.1 & No.2 pump stations | Mediterranean Sea | 1,547.5 |
| b. El-Gharbia drain | Mediterranean Sea | 1,198.6 |
| c. Tearra pump station | Mediterranean Sea | 381.8 |
| d. No. 7 drain | Burolus Lake | 344.5 |
| e. No. 8 drain | Burolus Lake | 539.4 |
| f. Nashout drain | Burolus Lake | 444.1 |
| g. Zaghloul pump station | Burolus Lake | 197.1 |
| h. No. 11 drain | Burolus Lake | 534.5 |
| Total | | 5,187.5 |
| 3. Western Delta | | |
| a. Edka pump station | Edka Lake | 210.6 |
| b. Barsiek pump station | Edka Lake | 259.4 |
| c. El-Tabia pump station | Mediterranean Sea | 77.9 |
| d. El-Kalaa pump station | Mariout Lake | 49.0 |
| e. El-Max pump station | Mediterranean Sea | 2,269.9 |
| Total | | 2,866.8 |
| 4. El-Fayoum | | |
| a. El-Rayan Valley and El-Wady drains | Daroum Lake | 383.9 |
| b. El-Batts drains | Karoun Lake | 259.8 |
| Total | | 643.7 |
| Grand Total | | 13,867.5 |

### 3. Use of inventory data

The Ministry of Irrigation has proposed to reuse drainage water for reclamation and cultivation, after mixing it in different proportions. The Reuse Project will provide an inventory of the quantity and quality of drainage water and will give an indication of the changes expected to take place with time, as well as the effect of sub-surface drainage and improved water management practices on the salt and water balance.

## C. Case studies and economic evaluations

### 1. El-Salam Canal Project

The El-Salam canal project plans to collect excess irrigation water from the Domieta Branch of the Nile at the Farasqour Barrage and the drainage from the Lower Serw pumping station and the Bahr Hadous Drain. The mixture will be used to irrigate newly reclaimed areas, firstly at the western side of the Suez Canal, an area of about 200,000 feddans (84,000 ha), and another of about 400,000 feddans (168,000 ha) on the east of the Canal.

It is assumed that 435 x $10^6 m^3$/year from the Lower Serw pumping station and 1,905 x $10^6 m^3$/year from Bahr Hadous will be mixed with Nile water in a ratio of 1:1 to give a total discharge of 4,680 x $10^6 m^3$/year for the Salam Canal.

The economic evaluation includes only the first phase (six years) and total costs will be about 266 million Egyptian Pounds (L.E.)[1/] and the agricultural benefits during those years will be about L.E. 247 million. During the following three years the total costs are expected to be L.E. 147 million and the benefits approximately L.E. 232 million.

It can be concluded that project benefits would exceed costs starting in year seven and would amount to about L.E. 175 per feddan per year.

### 2. Omoum Drain Project

Part of the water from the Omoum drain in the Western Delta will be used, mixed with irrigation water from the Nubaria Canal at El-Naser Canal inlet, in order to reclaim about 150,000 feddans (62,500 ha) in the West Nubaria area. About 1 million $m^3$/year from the discharge of Truga pumping station, Shireshra pumping station and the free discharge in Omoum drain will be reused.

The total costs of the project are expected to be L.E. 28,900 million and the benefits are still under study.

### 3. Reuse of the water of Batts Drain

It is planned to construct a pumping station to lift 124 x $10^6 m^3$/year from Batts drain to Bahr Wahby Canal. This would supplement the irrigation water to an area of about 23,000 feddans (9,580 ha) at the tail end of Bahr

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1/ $US1.00 = L.E. 0.70 (1985 period average).

Wahby Canal, where the water supply has always been short, in order to reclaim a new area of 10,000 feddans in the desert. Another area of about 10,000 feddans located north of Kom-Oshim will also be reclaimed.

All costs associated with project development were calculated to 1982. The construction period was assumed to be three years. It was estimated that L.E. 7.0, 16.5, and 7.0 million would be spent in each of the construction years, respectively. Annual costs are scheduled to begin in year four of the project and amount to L.E. 1.4 million.

After a detailed analysis it was concluded that new land irrigation benefits would in year five reach L.E. 14.5 million and remain constant throughout the project life. An increased livestock complement valued at L.E. 7.1 million was also determined and would start accruing benefits in year five. It is anticipated that upon full development, the area will maintain a rather high cropping intensity. Fodder, vegetables, and tree crops which are somewhat salt tolerant, and familiar to farmers, have been used in the study.

## Conclusion

Most of the drainage water which is of moderate quality for irrigation is lost to the sea. The Ministry of Irrigation of Egypt is implementing a plan to reuse this water for irrigation and reclamation of new areas. A reuse project is now under way to assess the quantity and quality of drainage water and to determine how and where this water might be efficiently reused. Three reuse projects are now under construction to reclaim about 760,000 feddans (317,000 ha) in the Nile Delta and El-Fayoum areas, reusing irrigation drainage water mixed in various proportions with Nile River water.

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## B. Jamaica: Rain stimulation programme for the Kingston and St. Andrew Water Commission, 1975 to 1977

by N. Gauntlett*

The Water Commission, with the prior approval of Government, initiated a rain stimulation programme in April 1975 by engaging the firm of North American Weather Consultants from Denver, Colorado. The firm carried out a cloud seeding programme, in co-operation with the Meteorological Office and the Air Wing of the Jamaica Defence Force (JDF), who provided the airplane and pilot.

The disastrous drought of the late 1960s followed by another severe drought of the early 1970s prompted the action taken by the Commission. In an effort to keep foreign exchange expenditures to an absolute minimum, the Jamaica Defense Force were instructed to provide plane and pilot. The commencement of the Programme was delayed, as the aircraft assigned to the project had to be sent to Miami for structural alterations and for the installation of a flare rack in the belly of the plane, and actual seeding did not commence until 26 May 1975. Both the Commission and the foreign experts were satisfied that the project was moderately successful, and felt that, had there been total dedication to the project, the result would have been more satisfying.

Cloud seeding opportunities were located and determined by the Meteorological Office's Weather Radar at Cooper's Hill, and the information was then telephoned to the Air Wing of the JDF where plane, pilot, Meteorological Office representative and the representative of North American Weather Consultants were standing by ready for action.

It had previously been decided that seeding of clouds would be confined to those clouds most likely to precipitate within the two prescribed target areas: the Hope River Valley above Papine and the Wag Water River Valley above Hermitage Dam.

Alas, because of the number of variable factors, a number of opportunities were lost due either to the unavailability of aircraft or pilot. Since the aircraft belonged to the JDF, Jamaica's national security force, security demands on the aircraft took precedence over the programme. In spite of this shortcoming, the exercise was deemed to be successful by the Commission and even by the Director of the Meteorological Office who previously had been most skeptical of the proposal.

North American Weather Consultant Services were engaged for a period of two months by the Commission and upon completion of their tour of duty were asked to submit an island-wide Cloud Seeding Programme proposal for Jamaica. They did submit the proposal, but it was never implemented.

During the low rainfall seasons of 1976 and 1977, the seeding programme was again initiated. During that time, however, the operation was carried out without the guidance of North American Weather Consultants. The terse reports from the Meteorological Office indicated that the incidence of "lost

*National Water Commission, Kingston, Jamaica.

opportunities" were greatly increased when the operation became wholly locally-manned. Often when opportunities presented themselves, plane or pilot or both were not available and sometimes when they were available there was no one from the Meteorological Office to fire the flares. In spite of this, a number of showers resulted from seeding activities although their effect was not as noticeable as it had been in the first seeding programme.

Although a National Cloud Seeding Programme was proposed, this had to be abandoned when the plane crashed and was damaged beyond repair. The plane has never been replaced. Another factor that sometimes affected utilization of opportunities was the availability of oxygen. The height at which seeding takes place really requires a pressurized aircraft. The Twin Otter, the only JDF plane then available with the capability of attaining the required altitudes, was not pressurized. Therefore oxygen bottles and masks had to be used instead, and sometimes oxygen was not available.

Obviously, therefore, the lessson learned from all of this is that all units vital to the mission must be dedicated to the mission and available at all times when opportunities are likely to be present, e.g., between the hours of 11 a.m. to 6 p.m. in the case of Kingston's target areas.

An examination of the rainfall records at the time of the first programme revealed areas, usually in the target area, where rainfall in excess of that currently being experienced in adjoining areas was being precipitated. This was confirmed by corresponding increases in streamflow into the main intakes, which was noticeably greater than would have occurred naturally. Inflow into the system over the two-month period was about 639 million gallons, of which some 141 million gallons went to increase storage. Another side-effect was the reduction in water demand on the days when rain fell in the distribution area, thereby reducing the draw-off on the system of water for gardens, etc.

In the view of the Commission's officers, this was a successful programme to the extent that the following recommendations were made: to continue the programme; to extend it island-wide; and to include possibly the use of ground generators of hydroscopic materials at suitable locations. This latter proposal followed upon a visit by a well-known authority on the subject of weather modification whose services were engaged to evaluate the recently completed seeding programme by North American Weather Consultants. He also concluded that the programme had been successful.

Rainfall improved after 1978 until 1981 when once again Jamaica was caught in the grip of another drought and in need of a cloud seeding programme. By that time the government had changed, and fear of flooding held sway over past experience.

As the Commission's officer in immediate charge of the programme, the author is convinced of the viability of rain stimulation as a safe water resource adjunct, provided that all the required elements for the success of the programmes are available and are dedicated to its success.

Such elements include weather radar, radio communications, a suitable plane (pressurized cabin and turbo-charged engines), flare rack and flares, a pilot and a meteorological officer, and on the ground a suitable network of gauging stations to evaluate and report on the success of the programme.

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