1974 - 1999
ESCWA

ECONOMIC AND SOCIAL COMMISSION FOR WESTERN ASIA

DEVELOPMENT OF NON-CONVENTIONAL WATER RESOURCES

UNITED NATIONS

Distr.
LIMITED
E/ESCWA/ENR/1997/9/Rev.1
8 June 1998
ORIGINAL: ENGLISH

ECONOMIC AND SOCIAL COMMISSION FOR WESTERN ASIA

DEVELOPMENT OF NON-CONVENTIONAL WATER RESOURCES

United Nations
New York, 1999

Bibliographical and other references have, wherever possible, been verified.

References to dollars ($) are to United States dollars, unless otherwise stated.

The Gulf Cooperation Council members are Bahrain, Kuwait, Qatar, Saudi Arabia, Oman and the United Arab Emirates.

99-0649

Preface

The Economic and Social Commission for Western Asia acknowledges with thanks the assistance of Mr. Adil Bushnak (Dar Al-Taqniya) of Saudi Arabia who served as ESCWA consultant for his substantive technical contribution during the preparation of this publication.

In accordance with the work programmed of the Energy, Natural Resources and Environment Division (ENRED) of ESCWA for the biennium 1996-1997, the Expert Group Meeting on Development of Non-Conventional Water Resources and Appropriate Technologies for Groundwater Management in the ESCWA Member Countries was held in Manama from 27 to 30 October 1997. The meeting provided a forum for government-designated experts on both conventional and non-conventional water resources to exchange views and examine ways and means to meet increasing water demand by developing additional freshwater resources, non-conventional ones in particular. These resources are required in order to bridge the water supply/demand imbalance resulting from drought conditions and excessive water utilization in all sectors.

The present technical publication was prepared to highlight the main issues discussed at the meeting and incorporates updated information and data in the national papers presented at the meeting. This publication was issued as an output under activity No. 3(a)(iii) entitled: "Development of non-conventional water resources in the ESCWA region", under the 1996-1997 work programme of ENRED.

The main objective of this study is to update the information available to decision makers about state-of-the-art technologies and present practices in water desalination and wastewater reuse. The study will review issues in technology and economics and examine current developments in the application of non-conventional water resources in the ESCWA region. Although rain harvesting is also an important technology, it is outside the scope of this report.

Chapter I of the study reviews various applied technologies in the desalination industry. Chapters II and VI provide brief economic appraisals of desalination technology and wastewater treatment and reuse. Technologies for wastewater treatment and reuse are the subject of chapter V. The environmental impact of both the desalination and wastewater industries is evaluated in chapters III and VII. Chapter IV presents an overview of the sources and uses of wastewater. A review of the applications of non-conventional water resources in selected ESCWA member States is presented in Chapter VIII.

The final chapter of the study presents the major conclusions and findings pertaining to the development of non-conventional water resources and cites practical recommendations to be considered at the national and regional levels in order to enhance this process.

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ABBREVIATIONS

ASR	Aquifer storage recovery
BH	Brine heater
BOD	Biochemical oxygen demand
BOOT	Build-Own-Operate-Transfer
BR	Brine recycle system
BRO	Brackish water reverse osmosis
BTU	British thermal unit
COD	Chemical oxygen demand
OC	Degrees Celsius
DO	Dissolved oxygen
E	E-coli
ED	Electrodialysis
EDR	Electrodialysis reversal
ESCWA	Economic and Social Commission for Western Asia
EPA	Environmental Protection Agency (United States of America)
GCC	Gulf Cooperation Council
GPD	Gallons per day
HRS	Heat recovery system
HFF	Hollow fine fibre
HTME	Horizontal tube multi-effect evaporators
l/c/d	Litres per capita per day
kg	Kilogram
KJ	Kilojoule
Km	Kilometre
kW	Kilowatt
Kwh	Kilowatt hour
m^2	Square metre
m^3	Cubic metre
m^3/d	Cubic metres per day
m^3/h	Cubic metres per hour
MBTU	Million British thermal units
MCM	Million cubic metres
MED	Multi-effect distillation
METC	Multi-effect thermal compression
MF	Microfiltration
mg/l	Milligrams per litre
MGD	Million gallons per day
ml	Millilitre
MS	Membrane softening
MSF	Multi-stage flash distillation
MVC	Mechanical vapour compression
O and M	Operation and maintenance
OF	Overland flow
µm	micro
OT	Once through
ppm	Parts per million
PR	Performance ratio
psi	Pounds per square inch
RO	Reverse osmosis
SANAX	Strong acid/sodium ion exchange
sp. gr.	Specific gravity
SR	Slow rate
SS	Suspended solids

SWRO	Seawater reverse osmosis
TDS	Total dissolved solids
THM	Trihalomethanes
TSE	Treated sewage effluent
TSS	Total suspended solids
TVC	Thermal vapour compression
UF	Ultrafiltration
$/m^3	United States dollars per cubic metre
VC	Vapour compression

INTRODUCTION

The territories of all ESCWA members (Bahrain, Egypt, Iraq, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, and Yemen) lie within arid or semi-arid regions characterized by limited conventional sources of water and a growing demand for their use. The scarcity of a natural supply of water has forced these countries to develop non-conventional sources, especially desalination and the re-use of wastewater. Therefore, in order to meet the excessive demand for water, the ESCWA member countries, especially the States that are members of the Gulf Cooperation Council, are heavily dependent on such non-conventional water resources as desalinated brackish and sea water and limited reuse of treated sewage effluent.

In the light of the limited water resources available to most ESCWA members, the augmentation of conventional water supplies by non-conventional water development techniques has become an overriding concern in the region. With the application of present technologies, desalination has become a viable alternative, matching to a great extent the high quality of freshwater resources. Therefore, brackish and seawater desalination may substantially reduce the overall scarcity of water in most of the ESCWA member States.

In this study, the term "desalination" is used to refer to the desalination of both sea water and brackish water.

Under the prevailing economic and technical conditions, sea and brackish water desalination is a practicable means of increasing the supply of freshwater. Hence, desalination offers an expedient solution to bridging the gap in areas short of water in most of the ESCWA member countries and has helped to meet the excessive demand for water over the last decade. In this respect, the ESCWA region is considered the world leader in utilizing the desalination industry.

Water obtained by the desalination of sea water is regarded as a net addition to the water budget of a country. It is therefore prudent to take this important factor into consideration when making financial evaluations of the cost of water desalination. Any quantity of high quality freshwater that is added by desalination to a water-use system can be considered to have multiple reuse effects. This means better management of the water product, permitting multiple reuse cycles in industry and in agriculture. Even more than two reuse cycles for the water are possible. It can be used first as potable water; it can then be reused as treated sewage for industrial cooling, as well as for other applications; and finally, it can be reused for irrigation.

In most of the ESCWA member countries, sewage effluent provides a convenient and economic source of water for irrigation. In the last decade there has been a significant move to minimize health risks and use the treated effluent with the highest possible efficiency. In addition to the wastewater being reused, the nutrients can be recycled through irrigation. It is noteworthy that at least eight of the ESCWA member countries operate modern wastewater reuse facilities to yield agricultural products; a great effort is being made to expand these facilities to bring more land under cultivation. Wastewater reuse will also help combat desertification and beautify cities by supplying water to irrigate ornamental trees and bushes and other greenery in public parks, as well as roadside trees and forests.

The two major concerns in utilizing such non-conventional sources as desalinated or reused water are costs and health. This study will demonstrate how developments in technology are reducing the costs to very competitive levels, which may make even seawater desalination economically viable for the production of high value agriculture crops. It is also possible to produce consistently high quality, safe water from wastewater. Long-term experience in utilizing reclaimed wastewater to augment groundwater reservoirs indicates that health risks can be controlled and water reuse is a viable source for arid regions.

I. DESALINATION TECHNOLOGY REVIEW

Desalination, in a general sense, is a process in which the salt content of saline water is reduced to the extent that it becomes suitable for purposes for which it could not originally be used. Desalination can be accomplished by the following means:

(a) Distillation processes in which water is separated from salt by changing it into vapour and then returning it to a liquid state by means of condensation;

(b) Membrane processes, which are selective transport methods in which salt or solvent is transferred away from a feed solution across some physical barrier without a change in the state of the solvent, in contrast to distillation or freezing. In reverse osmosis (RO) and electrodialysis (ED) this is done by allowing water or salt ions to move across semi-permeable membranes under the influence of pressure, as in RO, or under the influence of a direct electrical current, as in ED;

(c) Other processes, including ion exchange (chemical process), freeze desalination (thermal process) and membrane distillation.

Figure I shows the total capacity of plants sold worldwide over the last three decades for all processes.

A. DISTILLATION PROCESSES

Three major distillation processes are in use commercially. These are multi-effect distillation (MED), multi-stage flash distillation (MSF) and distillation with vapour compression (VC).

1. *Multi-effect distillation*

MED was the first desalination process to be developed for large scale application. In this process feed water is heated, then passed through a series of evaporators or effects. In the first effect, water evaporates by condensing live steam. Water vapour given off by the hot brine goes to the second effect where it condenses. The heat thus produced causes further evaporation of the brine in the second effect. The pressure in each succeeding effect is lowered to permit boiling and further evaporation at successively lower temperatures.

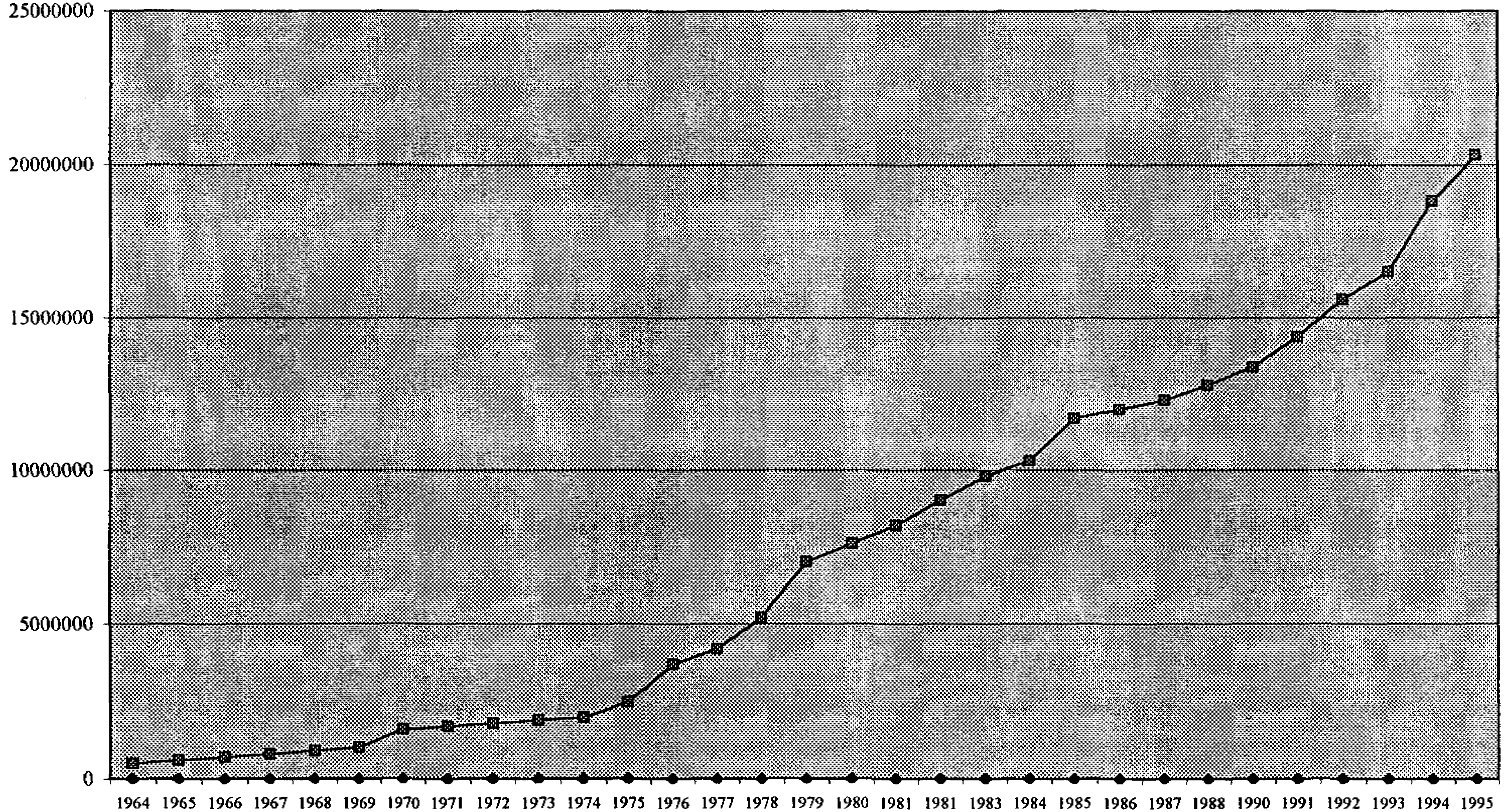
MED plants recover 40 to 65 per cent of the incoming water as desalinated product water. Although MED was a predecessor to MSF, it could not compete with it for long. Its contribution to the world market was 60 per cent in 1958 but after that dropped sharply, leveling off at its present value of around 6 per cent. This decline was primarily a result of operation and maintenance problems; the process was plagued by scaling and fouling, especially at high temperatures.

2. *Multi-stage flash distillation*

After being heated in a brine heater (BH), the feed to this process enters the first chamber or stage. When the hot brine is exposed to the reduced pressure in this chamber, it boils violently and a small portion of it instantaneously flashes into vapour. As the brine passes through successive stages operated at continually lower pressures and temperatures, more and more of the brine flashes into steam. The water vapour thus produced is then condensed on the outside of the tubes carrying the water proceeding towards the BH.

Typical MSF plants may contain from 15 to 30 stages. Increasing the number of stages means more capital cost. However, increasing the number of stages also increases the overall efficiency of the process, which may cause a decrease in the operating cost.

Figure I. Growth of sales of desalination equipment over the last 20 years



Source: Klaus Wangnick, *IDA Worldwide Desalting Plants Inventory No. 14* (International Desalination Association, 1996).

Two principal arrangements are used in MSF plants: the brine recycle system (BR) and the once through system (OT). The majority of existing MSF plants are of the BR type. It suits situations dictating relatively cheaper materials of construction as well as those where low cost treatment is favoured. However, the introduction of highly corrosion-resistant materials and advanced additives for scale prevention gives the process a favourable position (figure II).

The BR pump constitutes a sizeable portion of the capital cost. Fewer pumps are used in OT systems. In addition, a smaller heat transfer area is needed in OT systems owing to a lower boiling point.

The first commercial MSF plant was built during the 1950s in Kuwait. Since 1960, MSF distillation has dominated the commercial distillation market. However, with the introduction of RO in the early 1970s and continued growth of its market share, the MSF share of sold plants dropped from over 70 per cent of total world production capacity in 1969 to a little over 50 per cent by the end of 1991.

3. *Vapour compression*

In both the MED and MSF distillation processes, reduced pressure over brine is used to enhance vaporization. In vapour compression units, water vapour is collected and compressed. In this way the enthalpy and the temperature of the vapour are increased to the degree that the water vapour can be used as a heat source through its condensation in an evaporator or stage working at a temperature higher than that of the vapour before compression.

The energy required to increase the enthalpy can be introduced either by means of mechanical vapour compression (MVC), which is powered by an electric motor, or by inject ejectors, which are used to increase the enthalpy of steam by thermal vapour compression (TVC) (figure III).

As a result of compressor development during the last few years, many reliable types and sizes of compressors are now available. Axial compressors with up to 500,000 m^3/h inlet volume, compression ratios of 1.2 to 1.8 per stage, and stage efficiency of 90 per cent or higher are commercially available. When higher compression ratios up to 6 are needed, screw compressors can be used instead of multi-stage axial compressors. For smaller entrance volumes (less than 10,000 m^3/h), centrifugal compressors are recommended.

TVC consists of a supply box with an integral steam nozzle where steam pressure is transformed into kinetic energy, in the vapour entry region and diffuser region. The system is very reliable, as it has no moving parts. Its main disadvantage is low efficiency. If the real value of thermal energy used is considered, TVC may not be as uneconomical as the efficiency may suggest. Its advantage lies mainly in its low initial cost and low maintenance cost.

B. MEMBRANE PROCESSES

There are three major membrane desalination processes in use commercially, reverse osmosis, electrodialysis, and membrane softening (MS).

1. *Reverse osmosis*

When waters with different salinities are separated by a semi-permeable membrane, pure water from the low salinity side will diffuse across the membrane to the high salinity side until the concentration on both sides is equal, creating a pressure on the membrane called the osmotic pressure. Every solution has a specific osmotic pressure which is determined by the concentration of dissolved materials.

If a salty feed on one side of a semi-permeable membrane is subjected to a pressure higher than its natural osmotic pressure, the direction of flow is reversed and pure water will diffuse through the membrane, leaving behind water that is saltier (brine). For brackish water typical pressures are 200 to 500 psi, and for sea water 800 to 1200 psi.

Figure II. Typical multi-stage flash distillation flow diagram

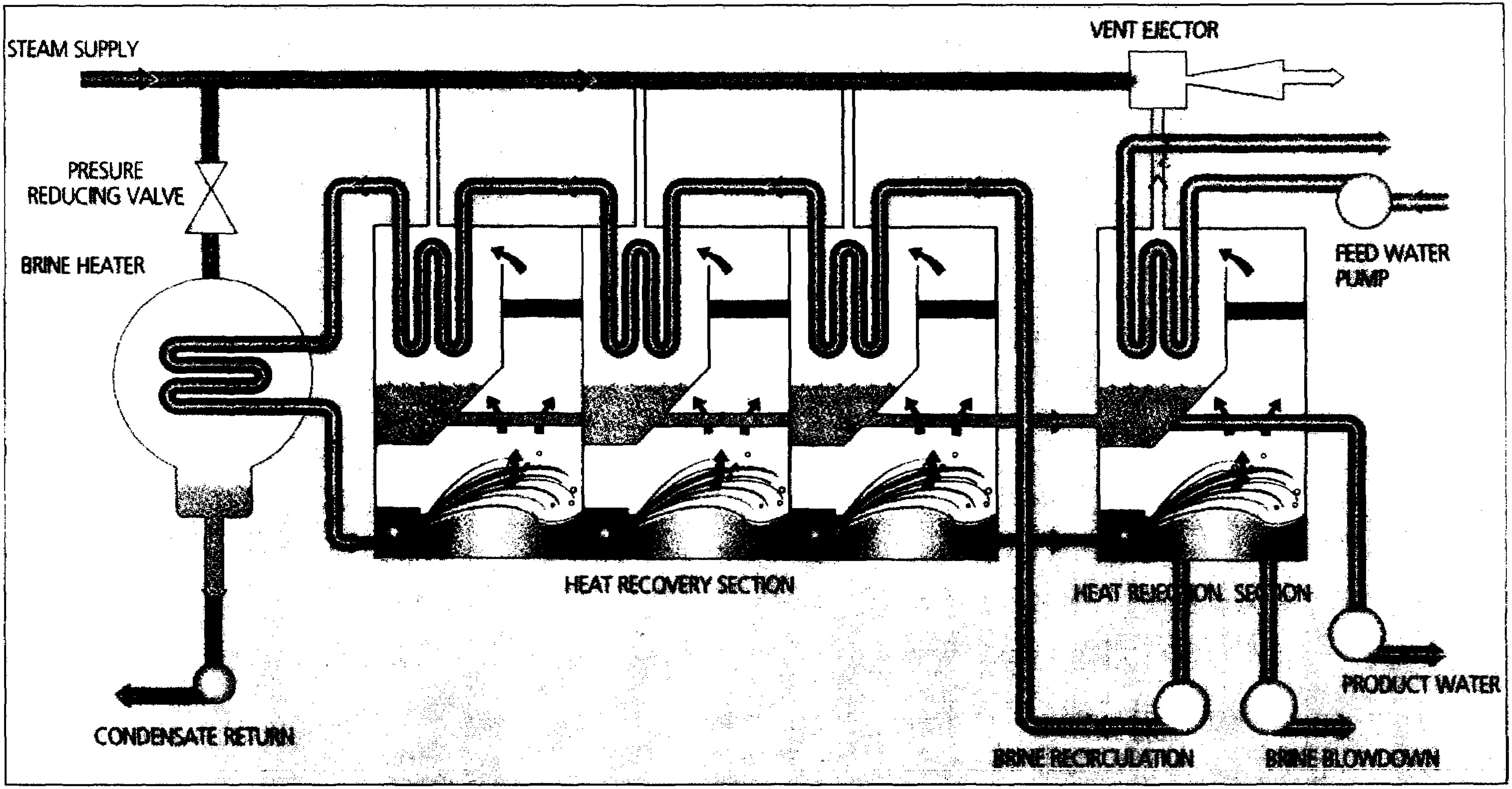
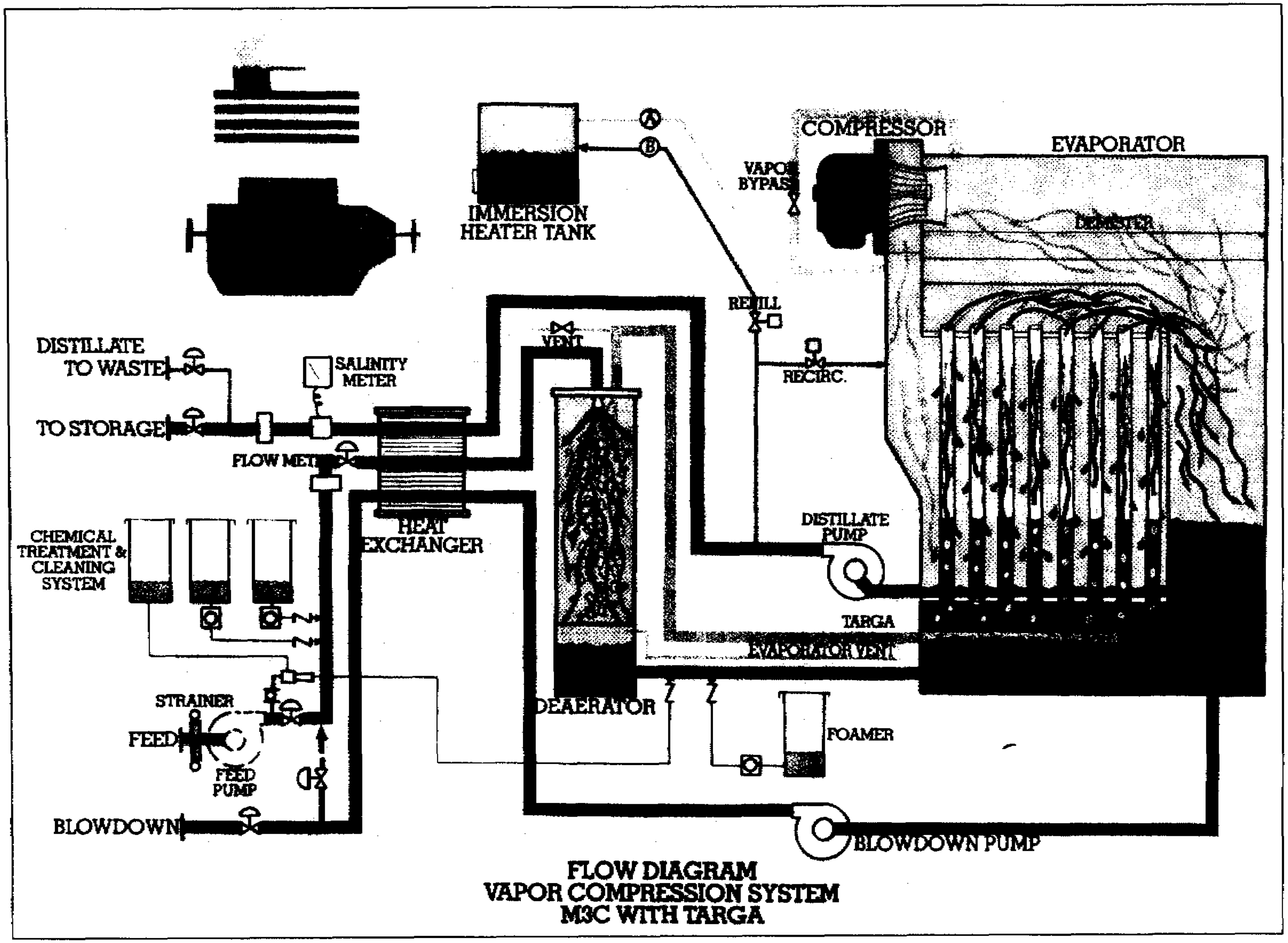


Figure III. Typical vapour compression system flow diagram



In the RO desalination process, the solution or feed is pumped into a pressure vessel containing a membrane. The most common commercial membrane modules are spiral-wound and hollow fine fibre (HFF) types. Each module type has technological and cost advantages and disadvantages. The most widely used modules today are the spiral-wound and HFF types (see figures IV and V).

Seawater reverse osmosis plants (SWRO) usually operate with about 30 to 50 per cent of the feed recovered as fresh water.

2. *Electrodialysis*

In ED, separation of the components of the ionic solution is brought about by placing across the path of a direct electric current sheets of membranes which are permeable to one type of ion and not the other. An ED desalination cell contains two different types of ion-selective membranes. One of the membranes is cation-permeable, allowing the passage of positive ions (cations), while the other, anion-permeable membrane allows the passage of negative ions (anions). If a direct current is established across a stream of saline water passing between a pair of these membranes, ions acting as carriers of electricity will migrate across the stream. The cation-permeable membrane permits positive ions such as Na+ to pass through while repelling negative ions, such as Cl-; the other membrane allows negative ions to go through, but not positive ions.

The membranes act as one-way check valves, preventing the re-entry of the ions they let through. Hence, the space between the membranes gets desalted while the streams on the electrode sides become concentrated with the penetrating ions. In ED desalting devices, many pairs of membranes are used between a single pair of electrodes forming an ED stock.

Electrodialysis is used primarily for desalination of brackish water. In seawater desalination, however, it has not been as successful as in brackish water desalination.

Early in the 1970s, the electrodialysis reversal process (EDR) was introduced. An EDR unit is basically the same as a standard ED unit except for the fact that at intervals of several times an hour, the polarity of the electrodes is reversed and the flows are simultaneously changed so that the brine channel becomes the product water channel and vice versa. Flushing of the stack and lines follows for 1-2 minutes. Then the unit resumes its normal operation. This helps break up and remove scales and other deposits from the membrane surface, allows the unit to perform with fewer pretreatment chemicals, and minimizes fouling.

3. *Membrane softening*

Nanofiltration, also known as membrane softening (MS), is a pressure-driven membrane process that can remove particles as small as 0.001 µm (RO can remove particles as small as 0.0001µm). Consequently, the MS membrane can reject organic molecules and can separate dissolved bivalent and trivalent ions (C+2a, M+2g, SO-14, PO-34, etc.). Typically, MS will remove 60 to 80 per cent of total hardness; over 90 per cent of colour; all pathogens, turbidity and pesticides; and most water contaminants known today (see figure VI).

MS is a process which provides full filtration and partial desalting. It is usually less expensive than RO and requires less energy or pressure to drive pure water molecules through an MS membrane. The process is increasingly used to provide potable water from coloured or contaminated surface water. Its water-softening capability is expected to be very valuable in future applications to increase the conversion ratio of MSF and RO plants.

C. OTHER DESALINATION PROCESSES

1. *Ion exchange*

In this process undesirable ions in the feed are exchanged with desirable ones by passing the water through granular beds of ion exchange resins. For industries requiring ultra-pure water, ion exchange resins are often used following RO or ED, in a process which is called polishing. It is also used for the removal of ions causing hardness of water (softening process). Ion exchange is a relatively simple process. Its cost lies primarily in the periodical regeneration or replacement of the resin.

2. *Freeze desalination*

Extensive work was done in the 1950s and 1960s to develop freeze desalination. In the process of freezing, dissolved salts are naturally excluded during the formation of ice crystals. Sea water can be desalinated by cooling the water to form crystals under controlled conditions. Before the entire mass of water has been frozen, the mixture is usually washed and rinsed to remove the salts in the remaining water or adhering to the ice crystals. The ice is then melted to produce fresh water.

Freeze desalination has many theoretical advantages. The main advantage is that the latent heat of freezing is about eight times lower than the latent heat of vaporization. This means that for the direct conversion process itself, eight times more energy is needed for evaporation than for freezing. Additional advantages include a minimal potential for corrosion and little scaling or precipitation. However, handling ice and water mixtures and their separation proved to be complex processes and hindered the development of freezing at the commercial level.

A small number of freeze desalination plants have been built over the past 40 years, but the process has not been a commercial success in the production of fresh water for municipal purposes. The most recent significant example of a freeze desalting plant was an experimental solar-powered unit constructed in Saudi Arabia in the late 1980s. The experimental work has been concluded, and the plant disassembled. At this stage, freeze desalting technology probably has a better application in the treatment of industrial wastes rather than in the production of municipal drinking water.

3. *Solar driven processes*

Solar stills are used effectively in some remote regions to provide sufficient drinking water. A general rule is that a solar collection area of about one square metre is needed to produce 4 litres of water per day. Careful operation and maintenance are needed to prevent scale formation caused by the basins drying out and to prevent glass or vapour leaks. The high cost of the still and the large area required to produce significant quantities of water make solar stills viable only for limited small users.

Desalting units that use solar collectors, such as solar ponds or photovoltaic panels, or wind energy devices to provide heat or electric energy have also been built to operate RO, ED and MED units. At the present time, using conventional energy to drive desalting devices is generally more cost-effective than using solar and wind-driven devices. However, appropriate applications for them do exist today. More applications are expected in the future, in view of the lower cost of these energy devices compared to conventional energy sources.

4. *Membrane distillation*

Membrane distillation was introduced commercially on a small scale in the 1980s. As the name implies, the process combines the use of both distillation and membranes. In this process, saline water is warmed to enhance vapour production, and this vapour is exposed to a membrane that can pass vapour but not water. After the vapour passes through the membrane, it is condensed on a cooler surface to produce fresh water. In liquid form, the fresh water cannot pass back through the membrane, so it is trapped and collected as the output of the plant.

Thus far, the process has been used only in a few areas. Compared to the more commercially successful processes, membrane distillation requires more space and uses considerable pumping energy per unit of production. Being essentially a distillation process, it is subject to some of the same performance limitations associated with that process.

Figure IV. Spiral membrane cartridge: cutaway view

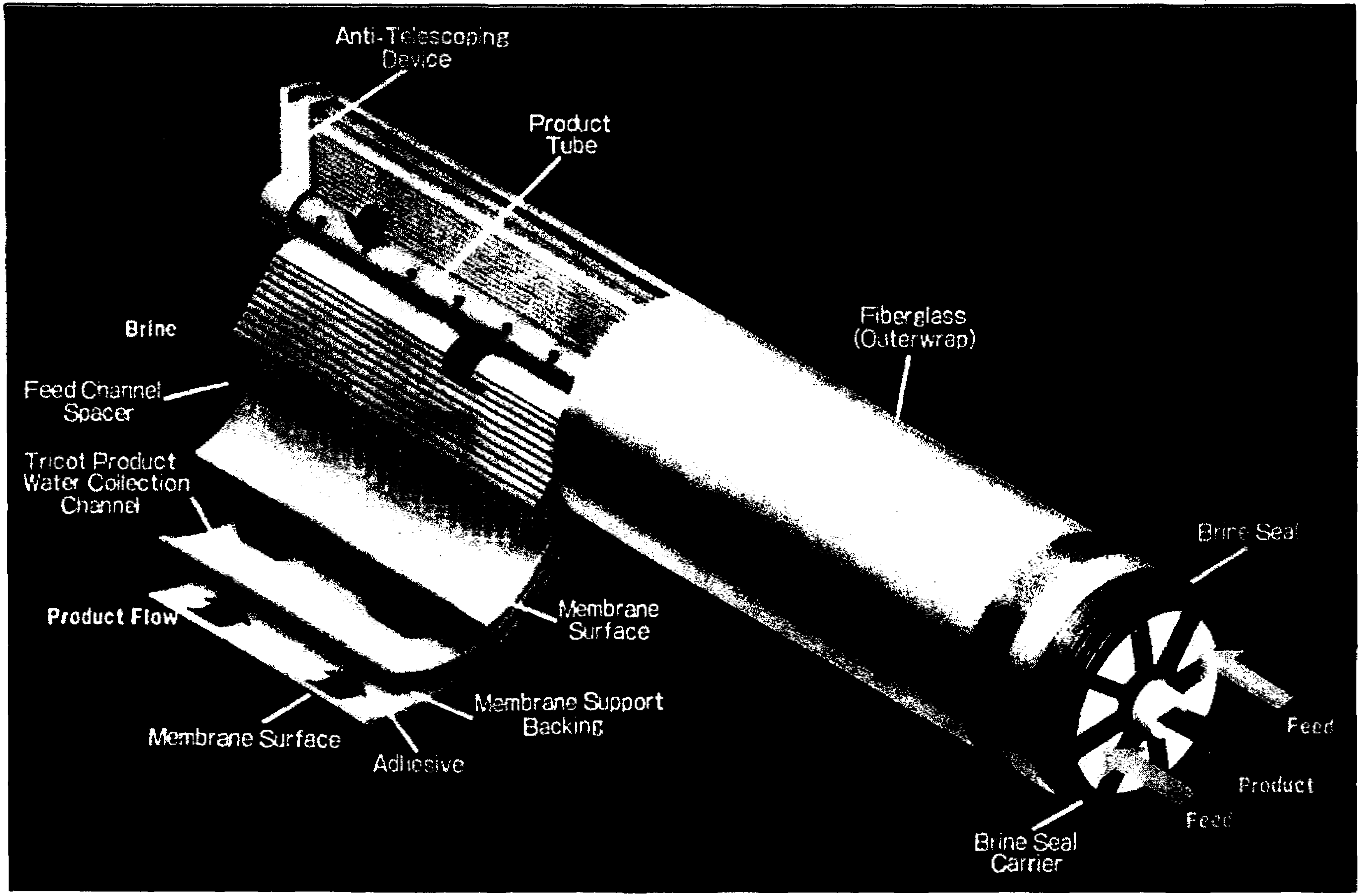


Figure V. Hollow fine fibre membrane: single and multiple cartridge configurations

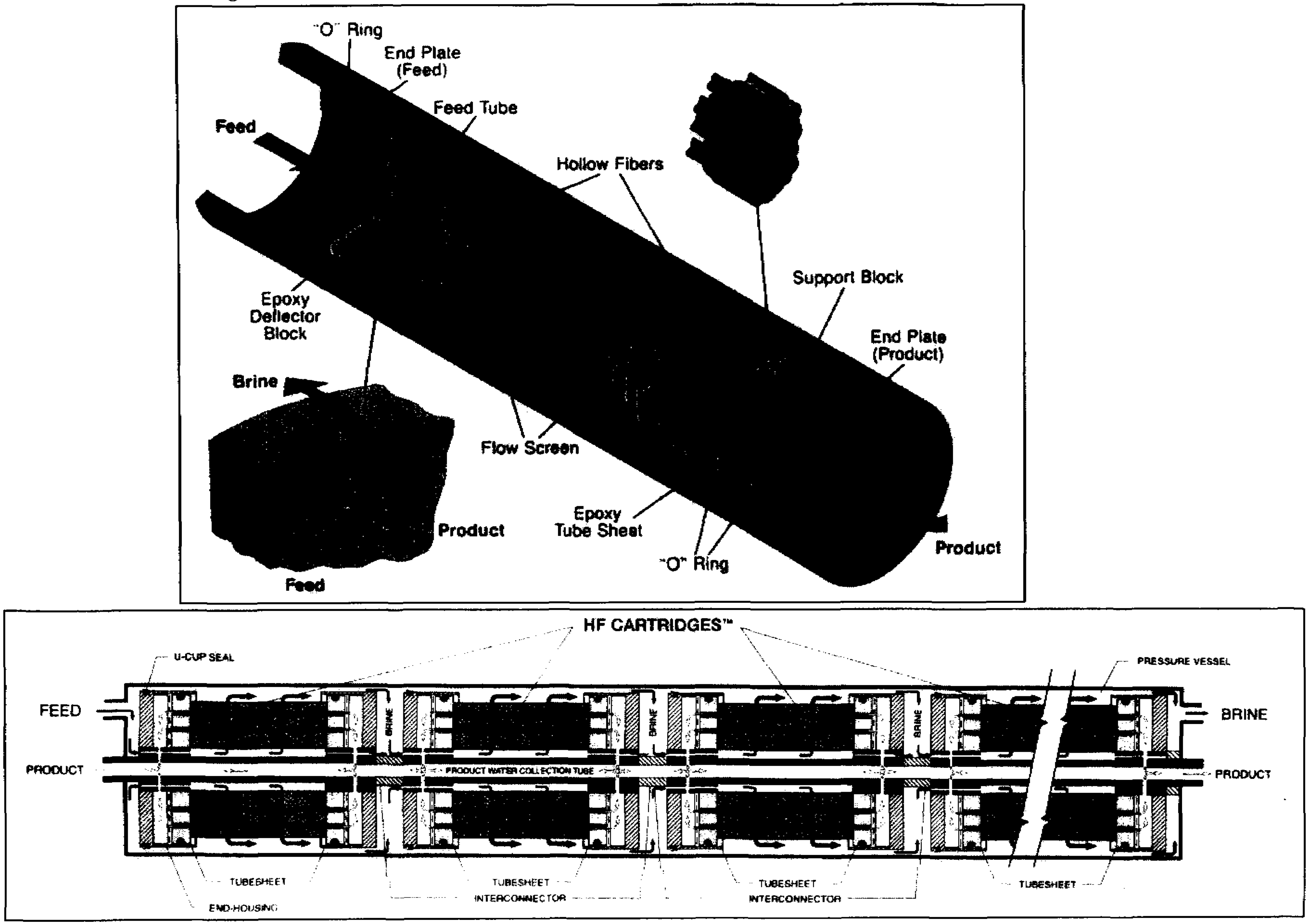
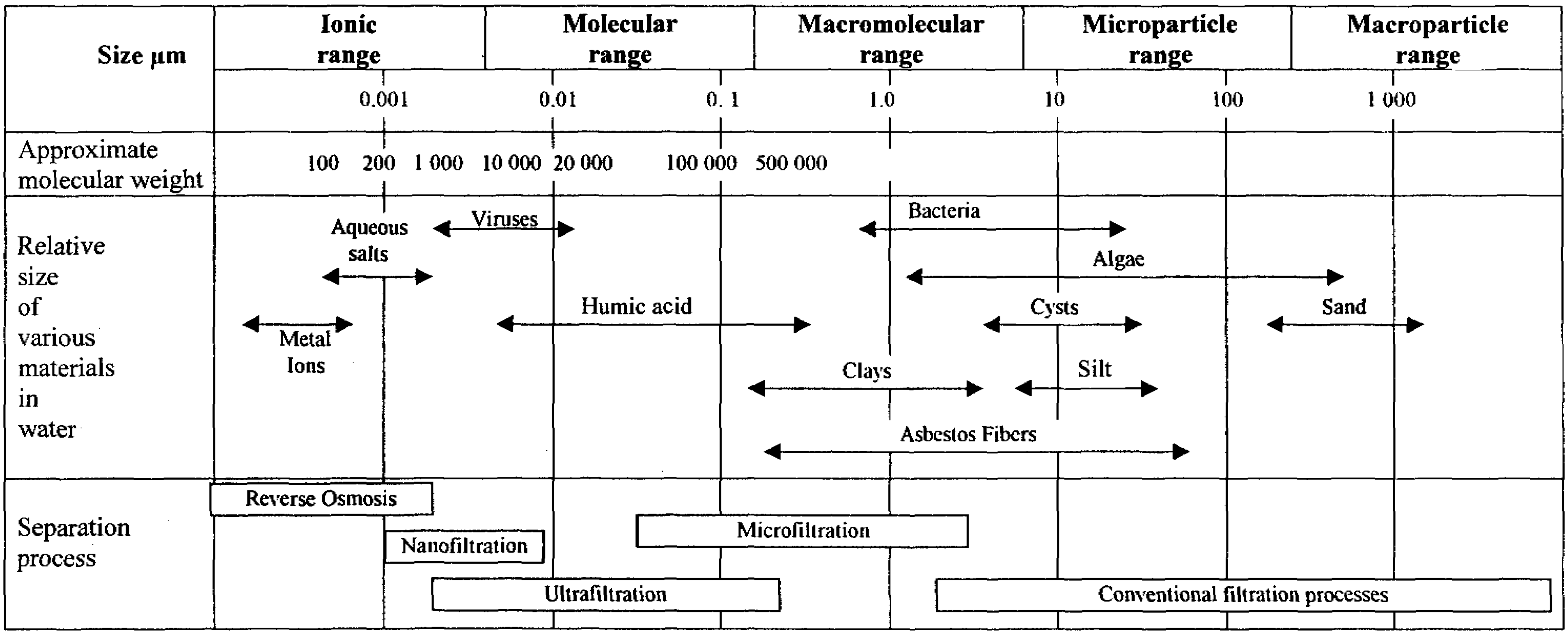


Figure VI. Selected separation processes used in water treatment and size ranges of various contaminants found in water



The main advantages of membrane distillation lie in its simplicity and the need for only small temperature differentials to operate.

Membrane distillation probably has its best application in desalting saline water where inexpensive low-grade thermal energy is available, such as from industries or solar collectors.

D. Hybrid systems

A hybrid system is a configuration made up of two or more desalination processes. The purpose is to combine the different cost-effective characteristics of each process productively. An example of a hybrid system is combining MSF with RO as in the Jeddah desalination facility. RO can be designed economically to produce low salinity water from sea water. RO product water is blended with the product water from the distillation plant which has a low level of total dissolved solids. This reduces the overall unit cost of water. An additional advantage of combining MSF and RO in dual purpose plants (plants producing water and electricity) is the relative ease of starting up or stopping an RO plant, allowing its use during off-peak power periods. RO can also be easily expanded on a modular basis, with minimum space, to meet incremental increases in water demand until a large scale distillation plant is built. Recognizing these benefits, Saudi Arabia is building RO plants to expand MSF facilities in Jeddah, Yanbu and Al-Jubail.

E. Process optimization

In selecting the required design parameters of a plant, some are determined by known physical and chemical constraints. For the others, there is a certain degree of freedom, which allows continuous or arbitrary determination. To achieve the best results, such determination is arrived at via optimization, in most cases according to economic criteria. For single-purpose plants the cost of the product is usually the dependent variable which should be minimized by the optimized design. In dual-purpose plants there might be several possible optimizations, depending on the customers for the two products. One conventional method is to design a dual-purpose plant to achieve minimum cost for the second product (the desalted water), using conventional costing for the primary product (electricity).

The number of parameters to be determined by optimization is quite large, as each plant and process has its own specifications. However, some are common to all seawater desalination processes, including the following:

(a) The ratio between the feed sea water and the desalted product water;

(b) The temperature range at which the separation takes place;

(c) The dimensions of the separation elements (such as the diameter and length of the heat transfer tubes in evaporation processes or the size of membranes in RO or ED processes);

(d) The number of effects, stages or passes in the various processes;

(e) The velocities of the fluid in each element;

(f) The flux. This is the most important parameter to be optimized in each process element. Flux is the heat transferred per unit area in heat exchange equipment; or the flow rate of desalted water per membrane unit area in RO elements.

All these parameters are also limited by physical or chemical constraints, but the optimal value of each usually differs from the extreme value.

The designer of a plant may wish to reduce the optimal capital investment, which is a function of heat transfer surface or membrane surface, by using a larger temperature difference, in the case of thermal processes, or pressure difference, in the case of RO, at the expense of energy cost and ease of operation. Various detailed methods for optimization are available in the literature.

F. Co-generation

In some situations, it is possible to use energy so that more than one use can be obtained from it as the energy moves from a high level to an ambient level. This occurs with co-generation where a single energy source can perform several different functions.

Certain types of desalination processes, especially the distillation process, can be structured to take advantage of a co-generation situation. Most of the distillation plants installed in the GCC countries operate under this principle. These units are built as part of a facility that produces both electrical power and desalinated sea water.

The electricity is produced with high-pressure steam to run turbines which in turn power electric generators. In a typical case, boilers produce high-pressure steam at about 540 °C or 1,000 °F. As this steam expands in the turbine, its temperature and energy level are reduced. Distillation plants need steam at about 120 °C or 248 °F or below, and this can be obtained by extracting the lower temperature steam at the low pressure end of the turbine after much of its useful energy has been used to generate electricity. This steam is then run through the distillation plant's brine heater, where it is condensed in the tubes, thereby increasing the temperature of the incoming seawater brine. The condensate from the steam is then returned to the boiler to be reheated for use in the turbine.

The main advantage of a co-generation system is that it can significantly reduce the consumption of fuel when compared to the fuel needed if two separate plants were in operation. Since energy is a major operating cost in any desalination process, this can be an important economic benefit in large-sized plants. However, recent developments in RO technology make this process very cost-competitive in relation to MSF even when both water and electric power are required. One of the disadvantages is that the units are permanently connected together and, for the desalination plant to run efficiently, the steam turbine must be operating.

This type of power and water production installation is commonly referred as a dual-purpose plant. Since all GCC countries are engaged in building up their total infrastructure, these types of installations fit in well with overall development programmes in these countries.

Other types of co-generation facilities supporting desalination can derive lower-cost steam from industrial processes or from burning solid wastes in an incinerator.

Since water can be stored, while electricity storage is not practical, excess electricity can be diverted to water production incorporating electrically driven sea water reverse osmosis and/or Vapour Compression and combined with the low pressure steam-driven technology of MSF or MED, realizing the advantages of an integrated hybrid plants. One method of employing idle power capacity is the use of electrically-driven RO or MVC plants in combination with aquifer storage recovery (ASR). ASR can be used to store excess desalinated water, and to provide strategic fresh groundwater storage or improve the quality of water in the basin.

G. Nuclear energy in desalination

The prospect of utilizing nuclear energy for seawater desalination on a large scale remains very attractive since desalination is an energy-intensive process which can utilize waste heat from a nuclear power plant or electricity produced by such plants. How the energy is produced makes no difference to the desalination process. However, the need to avoid any possible radioactive contamination of the product water, and the need to coordinate the implementation of major capital intensive power and water projects are some of the important aspects that should be considered.

It is well known that nuclear reactors are most competitive for large-sized electric plants (900 megawatts or larger) if low government-subsidized interest rates for capital and a national or regional power grid are both available. Very small-sized reactors suitable for dedicated use for a desalination plant may be commercially available but none have been built or commissioned to date. The availability, safety and security of nuclear fuel and the disposal of waste material need to be assured first in order to allow the market to open for such applications.

To improve the potential of nuclear energy for use in the process of desalination, other energy-intensive processes such as the production of salts from sea water need to be considered and evaluated as a cornerstone for the development of new industrial zones that would support energy-intensive industries.

II. DESALINATION ECONOMICS

The unit cost of desalinated water (in United States dollars per cubic metre or 1000 litres) ranges from about $0.25 to $3 or more, depending on several factors. This section reviews the impact of key technical and economic factors on the cost of water produced from desalination plants.

The major elements of the cost and their expected range as a percentage of the unit water cost are as follows:

Construction cost	30 - 60 per cent
Operation and maintenance cost	40 - 70 per cent
Energy	20 - 70 per cent
Labour, chemicals, spares	10 - 30 per cent
Membrane replacement	10 - 20 per cent

The typical construction cost of seawater desalination plants in the mid 1990s ranged between $1,000 and $3,000/m^3 of installed capacity, depending on plant size, site and design requirements. Table 1 lists typical unit construction costs based on formal bids or contracts over the last two decades, indicating that the unit cost of desalination plants is going down when inflation is accounted for. This is also true for brackish water desalination, in which the unit construction cost varies over a larger range because it is very sensitive to the quality of feed water and the cost of brine disposal. However, the cost of brackish water desalting equipment is usually less than 50 per cent of that of seawater desalting equipment.

The experience of such countries as Saudi Arabia and Kuwait confirms the unit water cost and unit investment cost given above. The average unit water cost from over 20 major municipal plants in Saudi Arabia is about $0.51/m^3 (1). However, when the cost of capital and the international cost of fuel are used, the Saudi average cost becomes close to one dollar per cubic metre. It is important to note that the unit cost of water produced at the huge Al-Jubail plant is only 68 per cent of the national average cost quoted above. A recent survey of more than 100 international experts in desalination arrived at a range of unit costs similar to that shown in table 1.

TABLE 1. TYPICAL CAPITAL COSTS FOR SEAWATER DESALINATION PLANTS

			Capacity		Capital cost (United States dollars)	
Year	Type	Location	MGD	m^3/d	$/GPD	m^3/d
1979	MSF	Jeddah III (Saudi Arabia)	23	88 000	15.00	3 936
1982	MSF	Jeddah IV (Saudi Arabia)	58	220 000	9.36	2 471
1985	MSF	Las Palmas de Gran Canarias (Spain)	6	27 727	4.80	1 267
1986	MSF	Assir, (Saudi Arabia)	30.7	116 128	4.17	1 102
1987	MSF	Al Khobar, (Saudi Arabia)	63	240 000	4.58	1 209
1989	MSF	Al-Khaburah (Oman)	12	45 454	11.25	2 970
1992	MSF	Medina-Yanbu II (Saudi Arabia)	38	144 000	5.00	1 264
1993	MSF	Al-Khobar III (Saudi Arabia)	63	240 000	4.72	1 417
1993	MSF	Shouaibah (Saudi Arabia)	112	454 000	3.76	1 047
1981	MED	St. Croix	3.75	14 200	4.00	1 056
1985	MED	Las Palmas de Gran Canarias (Spain)	6.0	22 727	5.71	1 505
1985	MED	Curaçao (Netherlands Antilles)	2.64	10 000	4.92	1 300

TABLE 1. *(continued)*

			Capacity		Capital cost (United States dollars)	
Year	Type	Location	MGD	m^3/d	$/GPD	m^3/d
1989	MED	Curaçao (Netherlands Antilles)	2.64	10 000	7.95	2 100
1978	SWRO	Jeddah (Saudi Arabia)	3.75	12 000	9.46	2 497
1981	SWRO	Key West (Florida, United States)	3	11 360	2.66	702
1984	SWRO	Ad-Dur (Bahrain)	12	45 450	4.09	1 080
1985	SWRO	Las Palmas de Gran Canarias (Spain)	6	22 727	4.23	1 117
1985	SWRO	Jeddah I Rehab (Saudi Arabia)	15	56 800	2.87	758
1987	SWRO	Jubail III (Saudi Arabia)	30	113 636	3.76	993
1988	SWRO	Jubail IV (Saudi Arabia)	24	90 910	6.42	1 695
1989	SWRO	Fujaira (United Arab Emirates)	2.4	9 090	6.25	1 650
1992	SWRO	Medina-Yanbu II (Saudi Arabia)	33.8	128 020	6.72	1 774
1992	SWRO	Jubail III (Saudi Arabia)	24	90 900	5.77	1 522
1995	SWRO	Dhekelia (Cyprus)	5.28	20 000	4.73	1 250

Most of the above factors are interactive. Each one is explained in detail below.

A range of costs for each type of component is given, rather than a general statement of desalination costs. The considerations in arriving at an estimate of overall desalination costs as well as the possible direction for future trends in these costs are reviewed below.

The key parameters that affect desalination cost can be grouped as follows:

(a) Feed water salinity and quality;
(b) Plant size;
(c) Energy factor;
(d) Process type and design;
(e) Infrastructure requirements;
(f) Intake type;
(g) Plant reliability;
(h) Operation and maintenance requirements;
(i) Finance cost;
(j) Environmental factors;
(k) Product water quality;
(l) Contractual issues.

A. FEED WATER SALINITY AND QUALITY

The source and quality of feed water are major factors in the cost of desalination. Desalting sea water, using either distillation or RO, can be from three to as much as seven times more expensive than desalting brackish water using RO or ED. In single purpose plants, distillation costs are high regardless of feed water salinity, owing to the larger amount of energy required to vaporize water. RO and ED costs are very sensitive to feed water salinity and quality. ED tends to be more economical than RO at salinities of less than 3,000 ppm, and less economical than RO at salinities greater than 5,000 ppm. All costs depend to a large extent on pre- and post-treatment requirements, particularly for RO.

The minimum energy needed for distillation is approximately proportional to feed water salinity. Membrane processes also require more energy as the feed water salt concentration rises. For RO, the pump pressure required by brackish water feed may range from 75 to 400 psi, while for sea water the range is from 800 to 1200 psi. With ED, not only does the ion transport current increase with salt concentration, but the high salinity concentrate also increases back diffusion of solute (concentration polarization) which to a large extent negates the electric current desalting action.

B. PLANT SIZE

Plant capital and operating unit cost decrease significantly as plant capacities increase up to about 3 MGD (11,366 m^3/d) for brackish water and 5 MGD (18,930 m^3/d) for seawater RO. Beyond these limits, costs generally decrease only slightly with increasing plant size (1). The rate of cost decrease in relation to plant size is more significant for thermal processes as compared with RO or ED.

Thermal methods are usually used for large- or medium-sized plants. MSF is most competitive for plants larger than 20,000 m^3/d. MED can be competitive for both medium- and large-sized plants, while VC is used mostly for small-sized plants. RO is the only process which can be competitive for any size plant.

Plants are usually composed of several units of equal capacity in order to reduce down time and loss of plant capacity. By process, the largest unit sizes sold to date are as follows:

Process	Largest Unit Capacity m^3/d	Competitive plant size		
		Small	Medium	Large
MSF	45 000			X
MED	18 000		X	
MED/TVC	6 000	X		
MVC	3 000	X		
RO - Sea water	8 000	X	X	X
RO – Brackish	10 000	X	X	X
ED	4 000	X		

C. ENERGY FACTOR

The contribution of energy to the running cost of desalting plants is very significant and varies from 20 per cent to 70 per cent. This variation is a function of plant performance ratio, energy cost, process type and process design. The form of energy depends on the process used. RO and MVC require only mechanical energy produced by pumps with compressors driven by electricity. Desalting one thousand litres of potable water from sea water by RO process requires from 3.5 to 12 Kwh, depending on recovery ratio, salinity of sea water, process design, and the type and efficiency of pumps and motors used. A well-designed, single stage, high energy recovery (45 per cent), large-sized unit with high equipment efficiency desalting Mediterranean water is expected to require approximately 4 Kwh/m^3. However, this design may not be the optimum for all sites nor for fuel cost. Desalting brackish water requires much less energy (from 0.5 to 2.5 Kwh/m^3) because of the lower salinity of the feed water. Using new low pressure (75 to 175 psi) membrane elements can reduce energy requirements for low salinity water from 25 per cent to 40 per cent. The other process driven only by electrical energy is MVC, which requires from 7 to 15 Kwh/m^3 depending on unit size and design.

For the distillation processes (MSF, MED, MED/TVC) the energy input is mainly in the form of steam or hot water. In addition, some electricity is required to drive pumps; for MSF this is from 3.5 to 6 Kwh/m^3 and for MED, from 2 to 2.5 Kwh/m^3. The heat requirements depend on the design, particularly on the number of effects and the performance ratio. The performance ratio, in turn, is related to the temperature of the heat source. For MSF, the specific energy consumption is in the range of 16 to 32 Kwh/m^3, and for MED from 11 to 23 Kwh/m^3 for a heat source inlet temperature of 120°C to 70°C. In MSF and MED processes, energy efficiency is increased by increasing the number of stages, or effects, in order to increase the amount of water produced from one unit of steam; that is, to increase the performance ratio (PR), which is defined as 1kg of product water per 1kg of steam. However, in practice, the efficiency gain is reduced by higher capital cost and unavoidable energy losses in each stage or effect (1). Table 2 compares the specific energy requirements of various processes. The electrical energy equivalent given in table 2 for thermal plants is not widely accepted in the industry, as the assumptions and methods of calculation used in converting thermal energy to electrical energy are not standardized. The total electric equivalent explains why distillation processes can not be energy-competitive unless waste heat is available, such as in co-generation plants. With fuel costs increasing over the expected life of plants (25 or 30 years), owners of new plants should give the energy factor due consideration. A recent study (3) analyzed the impact of oil prices on unit water cost and the results indicate that the cost of water produced by MSF doubles as the oil price goes from $0 to $30 per barrel, while sea water desalted by RO increases by only 20 per cent.

Cost allocations between water and power in dual-purpose plants has a major impact on unit water cost. This factor has been demonstrated by evaluation of actual cost data of an existing major plant in the Gulf (3). The results of the study demonstrate that the unit water cost ranges from $0.13 m^3 to $1.13 m^3, with various assumptions on allocation of the cost of components, cost of energy, and capital cost. Gulf countries use different cost allocation assumptions, as some consider water to be secondary product of dual purpose plants while others consider it to be a primary product. In an effort to standardize cost calculations, the Water Sciences and Technology Association invited representatives of all Gulf countries to a workshop in Bahrain. As a result of this gathering, a specific cost accounting procedure and cost allocation principle were recommended. This procedure was later adopted by the International Desalination Association, which sponsored the development of a computer software programme to calculate capital and total water costs for seawater desalination plants (3).

Non-conventional energy sources should be considered where fossil fuel and electric energy are expensive. Hydro power as well as wind, solar, nuclear and photovoltaic energy sources have all been used or proposed for desalting water. Future developments may make ocean thermal and tidal energy more appropriate in some locations.

D. PROCESS TYPE AND DESIGN

When seawater RO was first commercialized in the 1970s, MSF was less expensive than RO for desalting sea water. By the early 1980s the cost of desalinating sea water using RO or distillation (for plants over 20,000 m^3/d) had become roughly the same (3). This was a result of the decreasing cost of RO owing to improvements in membrane technology.

For plants smaller than 20,000 m^3/d, MED and VC are competitive with RO if a source of waste heat is available immediately adjacent to the desalination plant. RO and ED costs for desalting brackish water are about equal, but each has unique advantages and disadvantages. Distillation processes, especially MSF, have reached a mature stage of development and have proven to be very reliable. MSF plants with individual units that have a capacity of 578,000 m^3/d are under construction. Plants with a total capacity of 757,060 m^3/d (200 MGD) are operating successfully. Based on the advantages in size and technology offered by MSF, it is likely that this process will continue to be the workhorse of the industry for the next 10 years.

MED is well developed, yet specific aspects need to be improved such as the use of thin (3 mm thick) titanium tubing which increases heat transfer rates. However, the intrinsic weakness of MED is the passage of raw sea water through the plant outside the condensing tubes. This increases the difficulty of scale control and causes other operation and maintenance problems. Using low temperature MED to minimize the scaling problem reduces the energy efficiency of the process; however, this can be compensated by building more effects with low cost material and reduced energy losses. Vapour compression is combined with MED units to further enhance their efficiency. Developments in the design of compressors of higher capacities and better reliability have increased the competitiveness of mechanical vapour compression, which nonetheless is still limited by size of unit.

The membrane processes, RO and ED, have been employed to desalinate brackish waters in sizeable modules for more than 20 years. While the use of ED for sea water desalination has been very limited, by the end of 1991 seawater RO plants had attained accumulated world sales of about 900,000 m^3/d. Plants with a capacity exceeding 128,000 m^3/d have been constructed.

TABLE 2. ESTIMATED ENERGY REQUIREMENTS BY DESALINATION PROCESSES

	Process energy requirements (Kwh per cubic metre of product water)		
Process	Thermal	Electrical	Total electric equivalent
MSF	16-32	3.5-6	19.5-38 a/
MED	11-23	2-2.5	13-25.5 a/
MED/TVC	–	7-9	7-9
MVC	–	8-14	8-14
RO - Sea water	–	3.5-9	3.5-9 b/
Brackish water	–	0.5-2.5	0.5-2.5
ED - Brackish water	–	0.7-2.5	0.7-2.5

Sources: Adil Bushnak, "Water supply challenge in the Gulf region", *Desalination*, No. 78 (Amsterdam, Elsevier Science Publishers B.V., 1990); Congress of the United States, Office of Technology Assessment, "Using desalination technologies for water treatment" (Washington, D.C., Government Printing Office, OTA-BP-0-46, 1988); A. Bushnak, "Water desalination: the experience of the GCC countries" (Regional Symposium on Water Use and Conservation, Amman, 28 November – 2 December 1993, E/ESCWA/NR/1993/WG.1/WP.10).

Note: – Not applicable.

a/ The conversion of thermal energy to electric equivalents is based on the assumption that ingoing steam temperature is 110° C for MSF and 70° C for MED; thermal conversion efficiency is 0.25; and PR is between 8 and 12.

b/ This is the minimum energy requirement for large seawater RO plants with or without energy recovery. Smaller SWRO plants usually require more energy per unit water.

E. INFRASTRUCTURE REQUIREMENTS

The cost and availability of water storage, water transfer and other infrastructure required for building a desalination plant or delivering its water can be a major cost component. Such costs are usually a function of plant location and size. In locations where no infrastructure exists and the population served is small, or dispersed, it may be more cost-effective to build smaller or packaged plants.

The cost of product water will normally be very sensitive to both the distance and elevation of the raw water source or produced water destination relative to the location of the desalination facility. This is a result of capital and energy costs associated with pumping the water from the source to the plant. Key parameters that must be considered are the following:

(a) The large volumes of raw salty water that must be circulated imply significant capital costs for the associated ducts, pumps and valves. These costs increase proportionately with the distance from the source;

(b) As energy costs increase, the incentives for location of the desalination plant near the raw water source increase correspondingly;

(c) The location of the desalination plant near the point of introduction of the product water into the distribution system is an equally important consideration.

Sufficient water storage could be a major capital cost component for large desalination plants that feed expanding urban communities. Aquifer storage recovery technology has been applied successfully in different parts of the world and should be considered first to eliminate the need for building large storage reservoirs. ASR utilizes the geology to store huge quantities of water safely underground at minimum cost. Sufficient water storage in winter allows optimum baseload design and operation of large desalination plants in summertime when the efficiency of plants declines.

F. INTAKE TYPE

Seawater intake systems are designed to deliver the required seawater flow with the best available quality close to site. Seawater intake costs include intake pipes or channels, screens, intake basins and seawater pumps with all auxiliary equipment. These costs indicate that seawater intake could be one of the most expensive components in the plant. Therefore, due consideration has to be given to the design and location of the intake as well as to the location of the plant.

The main purpose of seawater intake systems is to provide good quality feed water free from seaweed, shells, sand and hydrocarbon contamination. To avoid suction of seaweed, the intake mouth should preferably be installed more than 10 m below sea level. This may result in the extension of intake pipes up to a distance of 12 km offshore. In addition, to reduce pollution from hydrocarbons the intake should be installed several metres below the lowest sea wave level. Owing to increasing seacoast pollution, simple onshore intakes with short channels are becoming increasingly rare.

Seawater intake is one of the vital components of the plant, so it should have a standby capacity. Intake pipes may be installed on the ground of the seabed but also above sea level with a vacuum-based siphon system.

Beach wells are a preferred type of intake for RO plants, as compared with an open seawater intake, if plant location and ground conditions allow the use of beach wells. The cost of developing a proper feed water source could be a large percentage of the total cost of a plant.

Seawater desalination plants need several times the volume of water they produce for processing and/or cooling requirements. The ratio between total seawater flow to product water varies by process type and process design. The following are typical ranges:

MSF	6-10
MED	4-8
VC	2-2.5
RO	2-4

G. PLANT RELIABILITY

The continuing trouble-free operation of a desalination plant is usually a key consideration that may be as important as cost. The reliability of any desalination plant is a function of proper operation and good design. Proper operation depends on the operators, experience, skills and training. Good design should compensate for or prevent operation errors, through sufficient instrumentation and control. Computer and digital controls allow full plant automation, which is highly desirable to increase the reliability of large plants.

A common measure of the reliability of desalination plants is the plant availability or plant load factor. This is the percentage of time the plant can operate at full capacity during a one-year period. It is a common practice in large plants to specify and to expect 90 per cent or better plant availability (8,000 hours per year). With good design and operation, plant availability may exceed 95 per cent over a one-year period. All plants need some shutdown time for routine maintenance, which accounts for the remaining percentage. A common approach to increasing plant availability is to have spares or duplicate copies of key items installed or in store ready for use when the operating item fails. However, this practice will increase initial capital cost.

The best approach to increasing plant reliability is through proper process design for the available water at the given site. Pretreatment of feed water before the brine desalting component is the most important consideration in plant design, especially for RO. Pretreatment for thermal units consists mainly of the use of acid or scale inhibitor to keep thermal efficiency as high as possible, which costs in the range of \$0.01 to \$0.03/m^3. For RO plants the cost of pretreatment is in the range of \$0.1 to \$0.25/m^3 of water produced. Pretreatment for RO usually involves several filters and chemical injections and may require clarifiers, activated carbon or other equipment depending on the chemistry and quality of the feed water.

The useful service life of a desalination plant is defined as the years over which the plant produces the water quantity and quality it is designed for. Large plants are designed for a service life of 25-30 years, while small or mobile plants are usually designed for 10 years. The selection of material and equipment specifications can greatly impact the capital and O and M costs required over the life of the plant.

H. Operation and maintenance requirements

The cost of labour, chemicals, spare parts and consumables such as filter media usually ranges between 15-30 per cent of running cost depending on plant size, process type and design. Labour cost varies typically from 1.5-3 per cent for large MSF plants, up to 20 per cent for small RO plants. Plant automation reduces the cost of labour, with the additional advantage of increased plant reliability.

The cost of chemicals is usually small for thermal plants but may reach 10 per cent of water cost for RO plants. Chemical consumption can be greatly reduced by proper process optimization for any given site. Availability of experienced and skilled labour to monitor plant performance becomes critical. High temperature distillation requires careful attention to scale control and corrosion prevention. ED, low temperature MED and low temperature VC require less operator attention and skill. The most demanding process is RO, for which operators have to be well-trained.

The annual cost of spare parts is usually about 1-2 per cent of the capital cost of the plant, excluding membrane replacement in RO plants, which averages 10-20 per cent of membrane cost annually. Membrane life expectancy has been improving continuously since 1970s. Most membrane manufacturers now provide five years' warrantee and the average expected life may exceed seven years for a well-designed and well-operated plant. Membrane cost is about 15-20 per cent of the cost of capital for a large seawater RO plant, and about 15 per cent of the total O and M cost, or 10 per cent of the unit water cost for large RO plants.

I. Finance cost

Desalination plants require major initial capital outlays that need to be depreciated over plant service life, which could be 30 years or more. Hence, the cost of capital has a significant impact on unit water cost since the capital contribution may reach 60 per cent of unit water cost. A recent analysis (3) of actual bid data for a large MSF desalination plant on the Gulf indicates a large variance in the capital contribution to unit water cost over plant life, which was specified as 25 years (see table 3).

For many countries, financing may constitute a major constraint in utilizing desalination technology as a result of the increasing scarcity of public financial resources. For these countries, innovative financing approaches, including private funding, will be needed to increase their supply of clean and safe potable water. Desalination plants are capital-intensive projects, the cost of which cannot be recovered unless their product is properly priced.

TABLE 3. COST OF CAPITAL IMPACT ON UNIT WATER COST FOR A LARGE DESALINATION PLANT ON THE GULF

Cost of capital (Annual rate – percentage)	Unit water cost (United States dollars per cubic metre)
0	0.10
10	0.24
15	0.65

Source: Adil Bushnak, "Water desalination: the experience of the GCC countries" (Regional Symposium on Water Use and Conservation, Amman, 28 November – 2 December 1993, E/ESCWA/NR/1993/WG.1/WP.10).

Note: Cost of energy used in above calculation is $0.25 per MBTU.

J. ENVIRONMENTAL FACTORS

The cost of meeting environmental regulations will become increasingly critical in desalination cost analysis and process selection to reduce air pollution and brine discharge. The major environmental impact of desalination plants is related primarily to the source of energy or type of fuel used to generate the steam or the electric power required for the process. Reducing or eliminating air pollution is expensive and is already well-established in power plants. Such pollution control equipment and cost will increasingly be an integral part of dual purpose desalination plants.

The experience of the GCC countries indicates that the water discharge effect of seawater desalination plants seems to be limited to a small area close to the brine outfall even for the very large plants. The process of dilution works fast to reduce the temperature of the hot brine, or balance its salt concentration or the chemicals it contains. Brine dilution can be enhanced at minimum cost with proper design of the discharge or outfall system.

The highest brine discharge cost is encountered in brackish water desalting at inland locations where there is no body of water or stream that can be used for brine discharge. Concentration of the brine to solid salts using properly instructed and lined solar evaporation ponds may cost \$0.30 to \$0.50/m^3 (see reference 12, based on 1985 estimate).

The alternative is injection into a deep well if the hydrology of the site allows such disposal. The cost of deep well injection ranged from 0.022 to 0.25/m^3.

More studies are needed to establish the impact of the environment on the cost of desalination. Biological fouling affects the performance of all desalination plants, especially RO plants at some locations.

K. PRODUCT WATER QUALITY

Any one of the distillation processes can produce comparatively pure water. Manufacturers typically submit bids containing warranties that the TDS will be less than 25 ppm and, in some bids, less than 10 ppm. The RO membrane process, on the other hand, will give twenty-five times higher TDS than the distillation processes from a seawater source in a single stage. In addition, TDS increases constantly from start-up to the end of membrane life. However, RO product water is within the desired levels of most international standards for drinking water. Hence, it needs minimum post-treatment. On the other hand, distilled water is very corrosive and must be post-treated before it is pumped to distribution networks, to prevent corrosion of distribution pipes. The cost of this post-treatment is more than that required for RO.

L. Contractual Issues

Potential owners of desalination plants should pay great attention to all contractual issues because they do affect the cost of desalination in many ways. Even if the owner or user of the product water opts for a build-own-operate-transfer (BOOT) contract instead of the conventional turnkey construction approach, attention should be paid to developing a consistent bidding strategy or policy as well as clear and concise specifications. Failure to be professional or fair at the bidding stage will increase the cost by eliminating proper competition. Early selection of a qualified consultant is essential to signal to all bidders the intent of the owner to build a reliable plant through complete specifications and their strict enforcement. The marginally higher initial cost will be recovered many times over the life of the plant.

As with other utilities, it is important to note the cyclic nature of the desalination business. Hence, the timing of bidding could have a significant cost impact for large-sized plants.

M. The Need for Integrated Solutions

Since water in arid regions is expensive regardless of the technology used to provide it, no country should embark on costly desalination capacity build-up before exhausting water management options. Rational use of high quality water, water conservation, innovative solutions and utilization of available natural assets should be considered first.

The use of desalination technology for long-term municipal water supply should be based on an integrated solution to reduce the cost of water now and in the future. Alternative water supply sources should be evaluated and compared to desalination cost, taking into account all cost parameters outlined above. For cities that need desalination, alternative sites should be evaluated, including intake and infrastructure cost. The desired sites should be reserved and protected from water pollution sources. Planning should ensure the availability of electric power, finance and manpower training.

The development of a local desalination industry to provide technical support and reduce the cost of import should be encouraged. Desalination technology can easily be transferred from other countries. The basic components of desalination technology such as engineering, metal fabrication, corrosion prevention, and process controls can also support other strategic industries such as electric power generation and petroleum industries.

N. The Cost of Alternatives

The two most common alternatives to desalination are water transport through pipelines or by tanker. The unit cost of a major trunk pipeline (38 to 40 inches in diameter) is about one million United States dollars per kilometre for level terrain. This unit cost can increase manyfold for mountainous terrain. Such cost can not be justified except where distances are short or when there is no alternative supply source.

Ocean bulk water transport by very large tankers costs a minimum of one United States dollar per ton. When the cost of water purchase, collection, storage and treatment at both terminal points is added, the unit cost of water is much greater than $\$2/m^3$ (20). The use of collapsible water bags may reduce some elements of the above cost but the risk of securing the supply route remains a major consideration in the reliability of the supply.

III. ENVIRONMENTAL IMPACT AND INTERACTION OF DESALINATION PLANTS

Potential ecological effects from desalination plants may result from the intake of sea water or the discharge of the remaining water (reject brine) back into the receiving body (19).

A. Intake effects

There are two types of intake effects: the impingement effect and the entertainment effect. As the water going into the plant is screened and filtered, aquatic organisms are removed. These organisms are either discarded or returned to the water body. This is called the impingement effect. The entertainment effect, however, takes place when smaller organisms passing through filters find their way through the process, where they get exposed to high temperature or pressure. These conditions affect them severely or even endanger their existence. Both of these effects may cause increased mortality rates for plankton of all types as well as fish. This in turn may result in reduced populations and hence reduced production and yield (3).

B. Discharge effects

Discharge effects may be divided into physical, chemical and biological effects. Physical effects refer to the effects of hot brine discharged from thermal desalination plants. Chemical effects result from increased brine concentration and treatment chemicals remaining in the brine as well as trace elements resulting from corrosion. Biological effects are related to changes in the biochemical oxygen demand (BOD) of the water, from its intake value to its final value at the discharge point. Dissolved oxygen concentration as well as micro-organism content may be affected by conditions prevailing throughout the plant.

Evaluation of these effects depends to a large extent on the physical characteristics of the marine environment. Environments that are semi-enclosed or inhabited by sensitive or high-value organisms should be avoided, if possible. If the environment is open and well mixed, then the effects will only be noticeable to within 300 metres from the discharge point.

1. *Thermal effects*

Thermal effects may be expected from distillation plants in particular, since they produce effluents which are between 5° and 8°C above feed water temperature. The extent of these effects depends upon the temperature level, the duration of thermal input and the type of biota present around the point of discharge.

Signs of thermal effects can be detected by changes in community structure, including the types of organisms, as well as changes in the characteristics of the individual species. To minimize these effects, it is customary to choose the plant site and design of the discharge system such that dissipation of thermal input takes place rapidly. The allowable increase in the weekly average temperature beyond 300 m from the point of discharge is 1°C. In addition, the daily temperature cycle should change neither in frequency nor in amplitude.

2. *Biological effects*

Biological effects that are caused by changes in physical or chemical characteristics of the environment are hard to determine, especially if these changes are relatively small. However, in general it is known that sea water taken into desalination plants possesses microbial flora, which is influenced by the physical and chemical conditions prevailing in the plant. Since these conditions vary considerably from one process to another, the discharge from different types of plants, although it has one thing in common, which is high salinity, differs in its biological characteristics. Effluents from distillation processes have lower dissolved oxygen content and higher dissolved organics, which result in a higher demand for biological oxygen. Reverse osmosis produces effluents with a lower content of organics and micro-organisms. In electrodialysis, a significant reduction in organics takes place, but microbial content may increase owing to the accumulation of organic material on membrane surfaces.

3. *Chemical effects*

Chemical effects derive from three sources: an increase in salinity, the chemicals used for treatment and the trace metals produced from corrosion. Increased salinity in discharge brine depends upon the original salinity of the feed water and the amount of water recovered. Recovery from brackish water by RO and ED ranges from 50 to 90 per cent, corresponding to a salt concentration in the brine from 2 to 10 times as much as its original value in the feed. From sea water, 20 to 65 per cent recoveries are attainable, depending on the process used for desalination, giving a concentration ratio of 1.25:3. While the concentration of rejected brine increases with an increase in recovery, its quantity decreases.

Studies on the effect of the chemical characteristics of desalination effluents on marine ecosystems are quite limited. However, indirect studies indicate that extremely high brine concentrations and high concentrations of heavy metal ions and chemicals may pose environmental problems.

Pretreatment is one step in desalination that is required in order to control scale formation and corrosion as well as in-plant micro-fouling. However, one has to strike a balance between reduced efficiency of the plant caused by scale build-up, corrosion and the accumulation of bio-fouling products on the one hand, and environmental effects, as pretreatment chemicals are added, on the other.

Intake water, which reflects the condition of the existing ecosystems, enters diverse processes. Depending upon the nature of the specific desalination process used, the water undergoes changes which are a function of the type of water treatment used. In distillation operations, there are three different methods in use: (a) polyphosphate treatment; (b) acid; and (c) high temperature antiscalant treatment. Along with the specific chemicals used in these three methods, one finds in the desalination effluents corrosion products resulting from the effects of water and dissolved gases as well as from the effect of treatment chemicals on the material of construction of the equipment used. This material may include heavy metal ions such as copper, iron, nickel and molybdenum. The amount of these ions is directly related to the pH of the water and the materials of construction. Consequently, in order to limit the potential for adverse effects on the ecosystem, it is advisable to control closely the pH of the water passing through the different stages of the process and adjust it at the end so that its value at the discharge point becomes as close as possible to its value at the intake. Build-up of heavy ions should also be prevented, either by using corrosion inhibitors or by using more resistant construction material. The level of concentration of heavy metals in the effluent should be limited and depends upon the characteristics of the local environment.

For discharging wastewater to coastal waters, the environmental protection standards of Saudi Arabia (18) provide guidelines similar to what is recommended above in this section. Saudi standards specify the maximum change from the typical baseline condition at the edge of a mixing zone based on a 30-day average, as follows:

pH	0.1 pH units
Total suspended solids	5 per cent
Total dissolved solids	5 per cent
Dissolved oxygen	5 per cent
Turbidity	5 per cent
Organic and non-organic pollutants	5 per cent
Total coliform	70 per 100 ml

A mixing zone is defined as one that will minimize adverse effects on designated beneficial uses. Adequacy of the mixing zone is determined on a case by case basis (34).

C. Inland disposal

Inland disposal is resorted to when desalination plants are far from large water bodies. This is usually the case with RO and ED desalination of brackish water. Options available for disposal in this case are:

(1) Pumping into lined evaporation ponds;

(2) Injection into deep underground formations;
(3) Farming or landscaping halophytes plants;
(4) Discharge through pipeline to sewers, rivers or other water bodies;
(5) Concentration as solid salts.

Cost plays an important role in choosing the method of disposal adopted. This cost may range from 5 to 33 per cent of the total cost of desalination, depending upon:

(1) Waste concentrate characteristics;
(2) Level of treatment before disposal;
(3) Means of disposal;
(4) Nature of disposal environment.

While deep well injection may cost 0.1-1.15 (in 1985 dollars per 1,000 gallons of desalinated water), properly constructed, lined evaporation ponds may cost more than deep well injection. Concentration to solid salts using solar evaporation may cost from $1.15 to $1.85 (in 1985 dollars per 1,000 gallons of desalinated water). With all types of land disposal methods, there is always a risk of groundwater contamination. This risk is lowest with concentration to solid salts.

D. QUALITY OF PRODUCT WATER

The most serious potential safety risk is the public consumption of desalinated water. Hence, strict quality standards must be maintained. These standards include the maximum allowable levels of toxic elements and the microbic content, as well as a certain minimum level of minerals that have to be present, since long-term usage of demineralized water may result in hemostasis (20). This is mainly a result of the washing out of body salts. Demineralized water may also have adverse effects on the cardiovascular, digestive and excretory systems. In correcting the mineral content of water, calcium bicarbonate is used owing to its significant effect on water taste. The optimum levels of important ions needed are 200 to 400 mg/l of chloride sulfate or sodium, 250 to 500 mg/l of bicarbonate or calcium salts, and 50 to 75 mg/l of calcium. None of the desalination processes gives desalinated water suitable for drinking, without post-treatment of some kind. The main objectionable properties may include: odour, corrosiveness, temperature and improper mineral and micro-elements composition. Post-treatment hence may include cooling if required, pH adjustment if necessary, purification from compounds, reduction of microbial content and reagents exceeding allowable limits, remineralization and fluorination as needed, and decontamination.

E. EFFECT OF THE ENVIRONMENT ON DESALINATION

Feed water may carry with it some of the characteristics of the environment prevailing in the vicinity of water intakes, which may affect the operation of desalination units to varying degrees.

1. *Biological fouling*

One example of the way in which desalination is affected by environmental conditions is biological fouling. Microfouling is a process in which the physical, chemical and bilogical conditions of sea water determine the rate at which the biomass increases. Microfouling of solid surfaces exposed to sea water is a well-known phenomenon. It is usually followed by macrofouling and corrosion. These phenomena significantly reduce heat transfer rates in thermal desalination processes and adversely affect the performance of RO membranes. The presence of raw sea water in tanks, conduits and filters is also a potential source for biofouling.

2. *Oil spills*

In the last decade oil spills have taken on dimensions large enough to warrant looking into their possible effects on desalination, since more than once they have occurred in the Gulf in the vicinity of intakes to desalination plants. Typical examples of such incidents are the 1984 Iranian Nairuz spill, and the 1991 Gulf war spill.

Spilled oil produces toxic effects on marine life, ranging from plankton to fish and even sea mammals. However, of concern in the present study is the possible effect on desalination plants.

Oil is a complex mixture of more than 140 different organic compounds, including straight and branched chain hydrocarbons and polycyclic aromatic hydrocarbons and their derivatives. When oil is spilled in the sea, a significant amount of low boiling fractions are lost by evaporation and many constituents, including phenols, dissolve in the water. In addition, part of the oil is dispersed. Oil dispersion is influenced by sea turbulence and water surface temperature.

In distillation processes, leakage of oil to the plant, whether dispersed or dissolved, increases the organic compounds content, which in turn increases the possibility of corrosion and a drop in the heat transfer rate. In reverse osmosis, the passage of organic compounds through the membranes will be selective. Low molecular weight compounds are more permeable than those with high molecular weight. Only about 5 per cent pass through. If the membranes get coated with oil, the water flux drops down. However, the presence of multimedia and micron filters safeguards the system. In addition, the use of activated carbon filters helps remove oil contamination.

The real threat to desalination plants is posed by the fraction of oil that is dissolved in water and hence finds its way into the system. After chlorination these organic compounds form very toxic materials which appear in the product water.

The feed water intake is one part of the desalination plant that deserves careful attention, especially if there is fear of contamination resulting from oil spills. Intakes vary from simple surface intakes to more costly deep intakes. To avoid pollution through hydrocarbons, intakes should be installed several metres below the lowest sea level (wave valley). Proper intake design helps to reduce the adverse effects of oil leaks, but does not solve the whole problem, since, as mentioned above it is the part of the oil going into solution that poses the real threat. Hence, careful monitoring of both inlet water and product as well as quick corrective measures are required.

IV. SOURCES AND USES OF WASTEWATER*

The three main sources of wastewater for reuse are municipal sewage, industrial effluents and agricultural drainage.

A. MUNICIPAL SEWAGE

Large quantities of wastewater are available from urban centres that have water supply and sewer networks. The average production of wastewater by the population in the ESCWA region is between 30 and 100 litres per capita per day (l/c/d) depending on household fixtures. If drainage or groundwater enters the sewer pipes, these rates may be as high as 300 l/c/d.

The constituents of sewage depend on the characteristics of the urban area. However, more than 90 per cent of the volume of wastewater is pure water. The key pollutants that affect the selection of the treatment process are suspended and settleable solids, ammonia and organic nitrogen, phosphorus, phenols, BOD total and faecal coliform. In addition, domestic sewage is infected by pathogenic organisms excreted by a small percentage of the population who have various diseases. The main pathogens are viruses, bacteria, protozoans and helminthic eggs.

B. INDUSTRIAL EFFLUENTS

Most industrial effluents are derived from washing, flushing, cooling, extracting, chemical treatment, impregnating and other similar operations. Their quantity and nature vary as they are products and processes of the plants from which they drain. Cooling waters are of large volumes discharged at high temperatures without any significant contaminants, but the effluents from some industries may be so loaded with organic and inorganic substances that they may be in the form of jelly. The effluents and the wastewaters of some industries are of greater concern for treatment than the domestic sewage of the same areas.

The tests that identify the characteristics and strength of domestic sewage cannot be applied to the analysis of industrial effluents without being supplemented by additional tests to evaluate more specific properties. For example, toxic wastes may have high COD values, but exert a low BOD, although much organic matter may be present. Industrial effluents, if possible, should be kept away and treated separately from municipal sewage. Toxic metals and chemicals may destroy the biological activity in municipal sewage treatment works and excessive concentrations of organic matter may place a heavy burden on these plants unless they are designed to deal with such excessive loads.

C. AGRICULTURAL DRAINAGE

An ample supply of water is available from the drainage from irrigation activities. Surface irrigation produces return flows as high as 35 per cent of the original supply volume, depending on the irrigation system, topography, soil type, crops and cropping patterns, and other factors. These return flows should be collected by an appropriate drainage system in order to assure proper crop production and protect the soil from salt accumulation. Continuous surface irrigation without appropriate drainage may cause a steady rise in groundwater level, eventually destroying the productivity of the soil.

Agricultural drainage water contains varying amounts of dissolved salts, fertilizers and pesticides. Its immediate reuse is not advisable for any purpose. Such water is usually diluted by a surface stream and partially purified by natural processes. The natural purification of polluted water is a slow process and depends on stream flow rate and velocity, the season, the degree of pollution and length of time before reuse. Sometimes, irrigation drainage is recycled by pumping it back to the head of the irrigation system. Reuse of drainage water for agriculture requires careful management of the soil and appropriate agricultural practices to prevent the accumulation of salts and chemicals in the soil. Typical treatment processes for agricultural

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* The material in chapters IV through VIII is taken primarily from an earlier comprehensive report by the Economic and Social Commission for Western Asia with some adaptation and updating (31).

drainage when no surface stream is available for dilution include agricultural ponds, sand filtration, membrane softening and desalination by reverse osmosis.

D. Municipal uses and requirements

Reclamation of wastewater for municipal and domestic proposes is practised in many countries of the ESCWA region. Direct potable use of reclaimed water is not recommended because it requires an advanced level of treatment and monitoring to reduce health risks. However, if wastewater is to be used for other domestic purposes, it should be treated to drinking water standards, shown in table 4, and distributed through a separate system for such activities as gardening or car washing.

Providing water of two qualities for households is common in only a few countries because it is difficult to maintain quality and avoid potential health risks. The most common practice in the ESCWA region is to use treated sewage for secondary municipal purposes such as street cleaning, fire fighting and watering public parks and roadside plants. In Saudi Arabia, about 22 per cent of the reclaimed wastewater is used, primarily by farmers outside Riyadh and Medina.

E. Industrial uses and requirements

Generally, water reuse in industry is achieved by recycling process water and using treated municipal sewage. Reclaimed water is usually used for cooling, production of steam and for the process requirements of some industries such as the production of construction material or mineral products. The total industrial uses of reclaimed wastewater in the ESCWA region remain very limited compared to the developed countries because of high costs and non-rigid environmental laws. Most of the uses in the region are for cooling in electric power plants and refineries.

The potential for industrial use of reclaimed water depends on the location and type of the industry. If a natural water supply is readily available, it is usually less expensive than recycling or treating municipal waste. However, with growing environmental concerns, the use of recycled water will increasingly be more attractive in the future, even when a conventional source is available.

The quality of water required for each industry has to be specified on a case by case basis. For example, the amount of total dissolved solids in feed water for boilers depends on the operating pressure of the boiler. Table 5 indicates water quality requirements for various industries.

TABLE 4. INTERNATIONAL DRINKING WATER QUALITY STANDARDS

	Maximum permissible contaminant level (In mg/l except as noted)	
Constituents	World Health Organization	Environmental Protection Agency
Arsenic	0.05	0.05
Barium	1.0	1.0
Cadmium	0.01	0.01
Chlorine	200-600	250
Chromium	0.05	0.05
Copper	0.05	1.0
Cyanide	0.05	-
Fluoride	0.7-1.7[a/]	1.4-2.4[a/]
Iron	0.1	0.3
Lead	0.1	0.05
Manganese	0.05	0.05

TABLE 4. *(continued)*

Constituents	Maximum permissible contaminant level (In mg/l except as noted) World Health Organization	Environmental Protection Agency
Mercury	-	0.002
Nitrate	50.0 (as NO_3)	10.0 (as N)
Selenium	0.01	0.01
Silver	-	0.05
SulpHate	250	250
Zinc	5.0	5.0
Colour (units)	-	15
Turbidity, NTU	-	1[b/]
Odour, TON	-	3
Foaming agents	-	0.5
Coliform bacteria (colonies/100 ml)	1	1[c/]
Radium, pCi/l	3	5
Endrin	-	0.002
Lindane	-	0.004
Methoxychlor	-	0.1
ToxapHene	-	0.005
2,4-D	-	0.1
2,4,5-TP Silvax	-	0.01
Trinalomethane	-	0.10

Source: Adil Bushnak, "Water supply challenge in the gulf region", *Desalination*, No. 78 (Amsterdam, Elsevier Science Publishers B.V., 1990), pp. 14-15.

Notes: A hyphen (-) indicates that there is no set standard for these contaminants.
NTU Nephel-metric turbidity unit.
pCi/l Picocurie.
TON Threshold order number.
a/ Varies with average annual maximum daily air temperature.
b/ Monthly average.
c/ Monthly average, by membrane filter technique.

F. AGRICULTURAL USES AND REQUIREMENTS

Using treated municipal sewage for irrigation of farms and public parks is widely practised in the ESCWA region. In addition to conserving precious natural water, sewage is especially attractive for reuse in agriculture because it has valuable nutrients that reduce the need for fertilizers. The salinity of reclaimed sewage is usually low, reducing the risk of salt accumulation.* However, sewage must be treated to a minimum level in order to avoid health risks. Table 6 gives the WHO standards for using treated wastewater in agriculture. Saudi Arabia's standards for using reclaimed wastewater in agriculture are shown in table 7. Restricted irrigation is allowed for landscape use outside major populated areas with certain limitations on the duration and method of irrigation. Untreated sewage should never be used, although it is still being applied in some ESCWA member countries without the approval of the authorities.

Industrial wastewater is not commonly used for agriculture because it typically contains heavy metals and toxic substances that are expensive to remove.

* The salinity of irrigation water must be below 750 ppm in order to avoid salt accumulation problems in most soils and for most plants. Severe plant growth and soil problems will occur if salinity increases beyond 3,000 ppm. Special soil conditioning, drainage and agricultural practices are needed in order to use high salinity water for irrigation.

All irrigation methods are suitable for reclaimed water with proper care and methods of treatment. The suitability of any given wastewater source for irrigation depends on the value of the products or plants that will be irrigated and the cost of optional sources of water. Modern desalination methods can be used to make any water suitable for irrigating high-value crops.

G. GROUNDWATER RECHARGE

The overpumping of groundwater in most countries and areas of the ESCWA region has reduced the groundwater level and increased the salinity of the aquifer. Long practice and studies of injecting treated wastewater have proven the technical and economic feasibility of groundwater recharge, used in the United States in California and Florida. No health effects have been noted after 20 years of this practice in the Los Angeles (California) metropolitan area and 11 years in the Monterey (California) area. Kuwait studied the feasibility of groundwater recharge and obtained encouraging results.

The hydrology of the ground must be suitable for successful recharge and recovery. Recharge is achieved by injection of treated water into the appropriate strata or by surface application when the soil strata makes this possible. In most applications in the United States, the recharged aquifer is used as a source of potable water at a suitable distance from the injection point.

The reduction of seawater intrusion in freshwater zones in coastal areas is another common use for groundwater recharge of wastewater. If the groundwater is also used for domestic supply, as is common in coastal areas, then tertiary treatment is essential before recharge.

H. AQUACULTURE PRODUCTION

Municipal wastewater contains nitrogen compounds and phosphorus, which are used by algae and aquaculture. These plants can supply nutrients for fish farming or serve as a source of protein for human or animal food supplements. However, special care must be taken to remove heavy metals and toxic material in order to avoid their transfer to humans or animals.

I. CONSTRUCTION USES

The ESCWA members need large quantities of water for the construction of roads and buildings. Reclaimed wastewater can be a good source for construction activities.

J. RECREATIONAL RESERVOIRS

Artificial lakes or surface reservoirs have been constructed in developed countries for the purpose of impoundment as well as for recreation. These reservoirs can also provide emergency water storage since wastewater must be treated to drinking standards.

TABLE 5. WATER QUALITY REQUIREMENTS FOR VARIOUS INDUSTRIES
(*Values in mg/l unless otherwise specified*)

Industry / Constituents	Once through cooling	Recirculation cooling	Boiler feed water	Petroleum and allied products	Oil well injection	Chemicals and allied products	Primary metal industries	Paper and allied products	Textiles	Tanning	Food and kindred products
Acidity (pH units)	5-8.3	2.0	8.2-10	6-9	6-8	6-9	6.5-8.3	-	6-8	6-8	0
Alkalinity	500	350	100	300	-	500	2	75	-	-	200
Aluminium	1	0.1	0.1	-	-	-	-	-	-	-	-
Aquatic growth	-	-	-	-	-	-	-	-	-	-	-
Arsenic	-	-	-	-	-	-	-	-	-	-	0.05
Bacteria	-	-	-	-	-	-	-	-	-	-	-
Faecal coliforms	-	-	-	-	-	-	-	-	-	-	-
Total coliforms	-	-	-	-	-	-	-	-	-	-	2.2
Barium	-	-	-	-	-	-	200/100 ml	-	-	-	1.0
Beryllium	-	-	-	-	-	-	-	-	200	-	-
Bicarbonate	600	24	120	480	-	600	-	-	-	-	-
BOD	-	-	-	-	-	-	-	-	-	-	-
Boron	-	-	-	-	-	-	50	-	-	-	-
Cadmium	-	-	-	-	-	-	-	-	-	-	0.01
Calcium	200	50	0.4	100	-	250	-	50	10	60	100
Chloride	600	500	-	300	-	500	-	75	100	250	200
Chromium	-	-	-	-	-	-	100	-	-	-	0.05

TABLE 5. (*continued*)

Industry / Constituents	Once through cooling	Recirculation cooling	Boiler feed water	Petroleum and allied products	Oil well injection	Chemicals and allied products	Primary metal industries	Paper and allied products	Textiles	Tanning	Food and kindred products
Cobalt	75	-	-	-	-	-	-	-	-	-	-
COD	-	75	5.0	1 000	5	-	-	-	-	-	-
Colour (units)	1	-	-	25	-	500	-	-	-	-	5.0
Copper	-	1	0.5	-	-	-	-	-	0.05	-	1.0
Cyanide	-	-	-	-	-	-	-	-	5	5	0.01
Fluoride	-	-	-	1.2	-	-	-	-	-	-	1.0
Hardness ($CaCO_3$)	850	650	1.0	900	-	1 000	100	100	25	150	200
Iron	0.5	0.5	0.3	0.3	1	10	-	0.1	0.1	50	0.2
Lead	-	-	-	-	-	-	-	-	-	-	0.05
Lithium	-	-	-	-	-	-	-	-	-	-	-
Magnesium	1	1	0.25	80	-	100	-	5.0	-	5	50
Manganese	0.5	0.05	0.1	0.3	-	2	-	0.05	0.01	0.2	0.1
Mercury	-	-	-	-	-	-	-	-	-	-	-
Molybdenum	-	-	-	-	-	-	-	-	-	-	-
Nickel	-	-	-	-	-	-	-	-	-	-	-
Nitrogen ammonia	1	-	-	10	1	-	-	-	-	-	-
Nitrate (as N)	-	-	-	8	-	-	-	-	-	-	10
Nitrite (as N)	-	-	-	-	-	-	-	-	-	-	0

TABLE 5. (*continued*)

Industry / Constituents	Once through cooling	Recirculation cooling	Boiler feed water	Petroleum and allied products	Oil well injection	Chemicals and allied products	Primary metal industries	Paper and allied products	Textiles	Tanning	Food and kindred products
Odour	-	-	-	-	-	-	-	-	-	-	0
Oil	No floating	-	-	-	-	-	1	-	-	-	-
Organics											
CCE	-	-	-	-	-	-	-	-	-	-	0.2
PCB	-	-	-	-	-	-	-	-	-	-	-
Oxygen	-	1	0.007	0.007	-	-	Acrobic	-	-	-	-
Pesticides	-	-	-	-	-	-	-	-	-	-	-
Phenols	-	-	-	0	-	-	-	-	-	-	0.001
Radionuclides	-	-	-	-	-	-	-	-	-	-	-
Selenium	-	-	-	-	-	-	-	-	-	-	0.01
Silica	50	50	10	20	15	-	-	20	-	-	50
Silver	-	-	-	-	-	-	-	-	-	-	0.05
Solids	-	-	-	-	-	-	-	-	-	-	-
Settleable	-	-	-	-	-	-	5	-	-	-	-
Suspended	5 000	100	5	30	2-5	10 000	30	-	-	-	10
Total dissolved	1 000	2	500	1 000	30 000	2 500	-	250	100	-	500
Sulfate	680	200	-	300	50	850	-	-	100	250	250
Temperature							75				
Turbidity	-	-	-	-	-	-	-	25	0.3-25	0	5
Vadium	-	-	-	-	-	-	-	-	-	-	-
Zinc	1	1	-	-	-	-	-	-	-	-	5

Notes: A hyphen (-) indicates that no restrictive values are specified.
CCE Carbon chloroform extract.
PCB Poly-chlorinated biphenyls.

TABLE 6. RECOMMENDED MICROBIOLOGICAL QUALITY GUIDELINES FOR WASTEWATER USE IN AGRICULTURE

Category	Reuse conditions	Exposed group	Intestinal coliforms (Geometric mean number per 100 ml)[a/]	Faecal coliforms (Geometric mean number per 100 ml)[a/]	Wastewater treatment expected to achieve the required microbiological quality
(A) Unrestricted	Irrigation of crops likely to be eaten uncooked; sports fields; public parks[b/]	Workers, consumers, public	1	1 000[b/]	A series of stabilization ponds designed to achieve the microbiological quality indicated, or equivalent treatment
(B) Restricted	Irrigation of cereal crops, industrial crops, pasture and trees[c/]	Workers	1	No standard recommended	Retention in stabilization ponds for 8-10 days for equivalent helminth and faecal coliform removal[d/]
(C) Localized	Localized irrigation of crops in category B if exposure of workers and the public does not occur	None	Not applicable	Not applicable	Pretreatment as required by the irrigation technology, but not less than primary

Source: FAO/RNE, "Proceedings of the expert consultation on reuse of low-quality water for sustainable agriculture", held in Amman, 15-18 December 1997 (Cairo, 1998).

Notes: In specific cases, local epidemiological, socio-cultural and environmental factors should be taken into account, and the guidelines modified accordingly.

a/ During the irrigation period.

b/ A more stringent guideline (200 faecal coliforms per 100 ml) is appropriate for public lawns, such as hotel lawns, with which the public may come into direct contact.

c/ In the case of fruit trees, irrigation should cease two weeks before fruit is picked, and no fruit should be picked off the ground. Sprinkler irrigation should not be used.

d/ Ascaris and Trichuris species and hookworms.

TABLE 7. SAUDI ARABIA MAXIMUM CONTAMINANT LEVEL FOR RESTRICTED AND UNRESTRICTED IRRIGATION WATER

Parameter	Standards: Restricted irrigation water	Standards: Unrestricted irrigation water
BOD	30 mg/l	10 mg/l
TSS	20 mg/l	10 mg/l
Faecal coliforms (MPN/100ml)		
Average duration	23	2.2
Maximum in any one sample	200	100
Intestinal nematodes, per litre	1	1

Source: *Water International Journal of SWRA, AIRE and AIREH,* vol. 22, No. 2, June 1997, p. 110.

Note: MPN: Most probable number.

V. WASTEWATER TREATMENT TECHNOLOGY REVIEW

During the treatment of sewage and industrial effluents, the concentration of polluting substances and organisms must be reduced. A wide variety of processes for achieving such reduction of contaminants are available. However, the sequence of processes that is used must be appropriate to the pollution situation and other conditions in a given country. Conditions in developing countries usually impose limitations on the choice of treatment. The ultimate uses of the treated wastewater dictate the degree and type of treatment to be adopted.

Wastewater for reuse is treated by the usual sewage treatment processes to a quality level that requires removal of most of the remaining suspended solids as well as disinfection. Because of its effect on the environment, wastewater treatment presents certain difficulties even under normal conditions; industrial waste discharges add to the complexities of the problem. The question of whether domestic and industrial wastewater should be treated together or separately largely depends upon the extent to which preliminary treatment is provided internally by factories. In many countries, urban drainage joins the municipal sewage and complicates the task of the treatment plant. Treating domestic sewage and industrial wastewater (and storm drainage water, if joining the system) together is a problem because each may have different characteristics and treatment requirements. The decision to centralize or individualize sewage treatment is largely dependent on problems associated with the economies of scale of treatment plants. The following factors are important: size and topography; population distribution and projections; location and volume of reclaimed water used; long-range development plans for the areas concerned; land-use planning programmes; type, size and condition of existing wastewater treatment system, if any; availability of operational staff; existing legislation and regulations; environmental impact assessment studies; energy considerations; and the economic evaluation of alternatives.

From the viewpoint of water quality management, it should be mentioned that larger plants generally yield better purification performance and more uniform effluent quality, and they can be operated more effectively. A treatment plant requires careful control and continuous supervision of the operators from the time that it goes into operation.

Although operation of wastewater treatment facilities may vary between countries or regions, some general control procedures and managerial approaches may be observed, including the frequency of control, effluent control, and training programmes for operators and supervisors. In many cases, control functions are performed by the operational staff of a plant, providing that the plant is operating efficiently and safely. Control activities should be supervised to ensure that effluent quality standards are being met.

Treatment processes suggested by the World Health Organization to meet various health criteria in wastewater reuse are presented in table 8. Conventional wastewater treatment begins with preliminary operations such as the screening of coarse solids and grit removal. Fats, oils, and grease are cause for special concern and they are usually removed through the use of grease traps and other facilities to catch the floating fats before they reach the sewage treatment complex. As mentioned above, treatment processes for wastewater reuse may be grouped into three stages: the primary, the secondary and the tertiary (advanced) treatment stages. These stages are described below.

A. PRIMARY TREATMENT

In a conventional municipal wastewater treatment plant, the principal step is sedimentation of settleable matter. In sedimentation ponds and tanks, about 90 per cent of the settleable solids present in raw sewage are removed. Generally, 40 per cent of the suspended solids are also removed in this process, and when coagulants are used, up to 70 per cent removal may be achieved. The retention time is usually 2 hours, during which 800 BOD is reduced to approximately 25 to 40 per cent, and some organic nitrogen, phosphorus and heavy metals are also settled out. However, most of the dissolved and colloidal matter present in wastewater cannot be removed in primary treatment, and the effect of such treatment on biological characteristics is also limited. Although sedimentation will remove some parasite eggs and cysts, salmonella and viruses will not be significantly affected.

B. SECONDARY TREATMENT

Effluent from primary treatment is subjected to one of three basic methods of treatment, where the degradable organic matter is consumed as food by bacteria in the presence of oxygen. The bacteria use some of the organic material for growth and multiplying. The remainder is oxidized to carbon dioxide and water. Some of the combined nitrogen and phosphorus present in the wastewater are absorbed by the bacteria at the same time. The most common secondary processes are outlined below.

The method of treatment by which the primary effluent flows over a packed bed of material, such as crushed rock or gravel, on which a surface film growth of bacteria is maintained is known as biological filtration (trickling filtration). Dissolved or suspended degradable organic matter adheres to the bacterial film and is consumed by the bacteria as food, thus producing carbon dioxide. As the bacteria grow on the bed, some of the film breaks off. It later settles out in a sedimentation tank and is removed prior to discharge of the effluent.

The second method of treatment is the activated-sludge process. In this process the primary effluent enters a tank and is agitated by a continuous stream of small air bubbles. Bacteria grow in suspension, consuming degradable material and multiplying, while oxidizing much of the remainder to carbon dioxide and water. The bacteria begin to flocculate near the tank outlet, having consumed much of the available organic matter. The bacterial flock is removed as sludge, and some of it is recycled to the tank inflow to maintain the bacterial activity.

The third method of conventional treatment is by means of a waste stabilization pond. Wastewater, with or without primary treatment, is retained in a pond or lagoon for periods of up to several weeks, where bacterial action removes the degradable material.

The first two methods are extensively used for the treatment of municipal and industrial wastes. In a properly designed system, the overall reduction of BOD and suspended solids to be expected from conventional combinations of primary and secondary treatment will be from 85 to 95 per cent. In addition, 60 per cent of non-biodegradable organics, 50 per cent of nitrogen, 30 per cent of phosphorus and a considerable proportion of pathogenic bacteria and viruses are also removed. In a properly designed and operated pond, well over 90 per cent of the polluting matter (in terms of its BOD) and many of the micro-organisms can be removed. Ponds have the advantage of providing a fairly high degree of treatment at a relatively low cost and with a simple operation. However, they require large spaces and are not practical for handling large amounts of wastewater.

Well-designed and operated secondary treatment plants will produce effluent with a quality level of 20 mg/l of BOD and 30 mg/l of suspended solids. While after disinfection this effluent may be suitable for some reuse applications, generally a tertiary treatment stage will be required.

Most dissolved inorganics are not affected by secondary treatment. Disinfection of disease-causing organisms still remaining in the wastewater may be accomplished using chlorine, bromine, iodine, heat, ozone or other means. Adequate disinfection requires rapid and complete mixing and minimum contact time. This is the last step in the treatment of wastewater, and thus, if advanced (tertiary) treatment is planned for, disinfection processes are applied as part of the tertiary treatment.

C. TERTIARY (ADVANCED) TREATMENT

After the secondary treatment, the following impurities usually remain in the effluent in varying concentrations, and are removed by various processes. Table 9 lists typical unit treatment processes used for tertiary treatment.

TABLE 8. TREATMENT PROCESS SUGGESTED BY THE WORLD HEALTH ORGANIZATION TO MEET GIVEN HEALTH CRITERIA IN WASTEWATER REUSE

	Irrigation			Recreation		Industrial reuse	Municipal reuse	
	Crops not for direct human consumption	Crops eaten cooked: fish culture	Crops eaten Raw	No contact	Contact		Non-potable	Potable
Health criteria	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		+	+		+++	+	+++	++
Denitrification						+		+++
Chemical clarification						+		++
Carbon adsorption						+		++
Ion exchange or other means of removing ions						+		++
Disinfection		+	+++	+	+++	+	+++	+++*

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 per cent of samples.
E. No faecal coliform organisms in 100 ml, plus no virus particles in 1,000 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 +++ are essential. In addition, one or more processes marked ++ are essential, and processes marked + may sometimes be required.

* Indicates free chlorine after 1 hour.

(1) Suspended and colloidal solids constitute only 20 to 30 per cent of total organic matter in secondary effluent, but account for most of the biodegradable organic matter present. These solids are mostly debris from dead cells, poorly or non-flocculated bacterial cells and extracellular insoluble products of bacterial metabolism that remain after secondary treatment and can be removed by any of several relatively simple processes including microstraining or microscreening sand filtration, and by tube settlers consisting of tubes of various cross-sectional configurations inclined at 45 to 60 degrees to the horizontal, in which the suspended solids settle.

(2) Plant nutrients, principally inorganic nitrogen compounds, occur as ammonia (NH_3) or ammonium ion (NH_4), nitrate ion (NO_3) and nitrite ion (NO_2), and phosphorus as the phosphate ion (PO_4).

A considerable portion of phosphorus is introduced into wastewater as a constituent of detergents and other cleaning aids, and some of it appears as a product of the degradation or organic wastes. Phosphate may be undesirable in water used in industry, where it may interfere with softening procedures and cause scaling on heat surfaces. It also stimulates growth of algae in impoundments. A number of removal processes exist, including chemical precipitation and bioprecipitation, and activated sludge modification (if not done in the secondary treatment stage). With all conventional primary and secondary treatment, urea and organic compounds of nitrogen are converted to ammonia and, under favourable conditions, to nitrite and then to nitrate. Some nitrogen is normally released in the elementary gaseous form during treatment. The presence of ammonia may lead to corrosion and reduce the efficiency of chlorination. Nitrate leads to eutrophication of streams, lakes and impoundments, and causes concern when reduced to nitrite.

(3) Refractory organic matter, such as pesticides, which is resistant to biological treatment, and the products of bacterial metabolism can be reduced to very low concentrations by activated carbon techniques.

TABLE 9. IMPORTANT CONTAMINANTS IN WASTEWATER AND THE UNIT OPERATIONS, PROCESS AND TREATMENT SYSTEMS USED FOR THEIR REMOVAL

Contaminants	Reason for importance	Unit operation, unit process, or treatment system
Suspended solids	Suspended solids can lead to development of sludge deposits and anaerobic conditions when untreated wastewater is discharged in the aquatic environment.	Sedimentation Screening Filtration variations Flotation Chemical-polymer addition/sedimentation Coagulation/sedimentation Land treatment systems
Biodegradable organics	Composed principally of proteins, carbohydrates and fats, biodegradable organics are measured most commonly in terms of BOD (biochemical oxygen demand) and COD (chemical oxygen demand). If discharged untreated to the environment, their biological stabilization can lead to the depletion of natural oxygen resources and to the development of septic conditions.	Activated-sludge variations Fixed-film: trickling filters Fixed-film: rotating biological contractors Lagoon variations Intermittent sand filtration Land treatment systems Physical chemical systems
Pathogens	Communicable diseases can be transmitted by the pathogenic organisms in wastewater.	Chlorination Hypochlorination Ozonation Ultraviolet light Land treatment systems

TABLE 9. (*continued*)

Contaminants	Reason for importance	Unit operation, unit process, or treatment system
Nutrients	Both nitrogen and phosphorus, along with carbon, are essential nutrients for growth. When discharged to the aquatic environment, these nutrients can lead to the growth of undesirable aquatic life. When discharged in excessive amounts on land, they can also lead to the pollution of groundwater.	Nitrogen removal Suspended-growth nitrification and denitrification variations Fixed-film nitrification and denitrification variations Ion exchange Breakpoint chlorination Land treatment systems
Refractory organics and organic priority pollutants	These organics tend to resist conventional methods of wastewater treatment. Many of the priority pollutants pose health risks. Typical examples include surfactants, phenols and agricultural pesticides.	Carbon adsorption Tertiary ozonation Land treatment systems
Heavy metals	Heavy metals are usually added to wastewater from commercial and industrial activities and may have to be removed if the wastewater is to be reused.	Chemical precipitation Ion exchange Land treatment systems
Dissolved inorganic salts	Inorganic constituents such as calcium, sodium and sulfate are added to the original domestic water supply as a result of water use and may have to be removed if the wastewater is to be reused.	Ion exchange Reverse osmosis Electrodialysis

Source: Adapted from Metcalf and Eddy, *Wastewater Engineering: Treatment, Disposal, Reuse*, 3rd ed. (McGraw Hill).

(4) Dissolved minerals such as sodium chloride and other mineral salts are not normally removed in conventional treatment plants. Half of the total mineral content is already present in water supplies and the other half is added during use. The nutrient ions, discussed in this report, are actually inorganic substances. The other dissolved minerals include sodium, potassium, calcium, magnesium, chloride, bicarbonate, sulfate, silicate, iron, copper, zinc and other less widely distributed metallic ions contributed by industrial processes. Removal processes include reverse osmosis, electrodialysis and ion-exchange demineralization.

(5) Pathogenic organisms are largely removed during primary and secondary treatment; however, removal is not total. Disinfection is the last process for treatment of any pathogenic organisms remaining in wastewater. Chlorine is the most generally used disinfectant and so far has played a major role in the prevention of water-borne diseases. Ozone is also used as a disinfectant, and lessens the colour of effluents, but it is more expensive than chlorine. Other disinfection methods are the use of chlorine dioxide and ultraviolet radiation. It is difficult to kill all the viruses remaining in the effluent, and not all types of viruses have yet been identified. Owing to the impossibility of complete removal of pathogenic organisms, the uses of purified effluents are limited and should be restricted. Table 10 lists important considerations in the selection and evaluation of tertiary treatment processes.

The basic sewage treatment processes of preliminary, primary and secondary treatment are necessary before the effluent can be discharged of into the sea or receiving streams, lakes or elsewhere. In places where such a treatment plant exists, the secondary effluent can be considered the source for reuse applications, and all subsequent treatment can be designed based on the application requirements. If a specific plant is planned, then some steps in the secondary and tertiary treatment processes can be mixed in a train of unit processes.

Secondary biological treatment for removal of ammonia can be taken as a example of the effect of reuse applications on the design of the treatment plant. Agricultural requirements with respect to nitrogen should be ascertained first. Subsequently, a decision should be taken as to whether the ammonia present in the sewage should be nitrified by treatment and, additionally, whether the nitrate so produced should be denitrified to eliminate much of the nitrogen from the effluent. Although for irrigation purposes it makes no difference if nitrogen is available as ammonia or nitrate, nitrification produces a much higher quality of treated effluent and is often preferred as a method in spite of its higher cost.

D. ADVANCED MEMBRANE TREATMENT

Recent commercial developments in membrane products provide very attractive alternatives to conventional secondary and tertiary treatment processes. It is possible now to build relatively low cost membrane systems that can produce high quality water, free from all biological and organic pollutants and most inorganic contaminants, from raw wastewater in a single process. Microfiltration (MF) and ultra-filtration (UF) are pre-driven physical separation processes that can replace conventional physical, biological and chemical processes, which require more space, material and labour to provide the same performance.

Microfiltration of membrane processes (see figure VI) usually has a pore size ranging from 0.05 to 5µ. As a consequence of its large pore size, it is used primarily for particle and microbial removal and can be operated under ultra-low pressure conditions (10 to 30 psi). While MF can remove all bacteria, it can not remove all viruses.

Ultrafiltration is a process using a denser membrane capable of rejecting all colloidal particles, biomolecules, viruses, bacteria and oil emulsions. It is possible at present to produce an MF membrane that can reject particles with a molecular weight of 1,000 (19). UF and MF membranes are usually classified by their achievable molecular weight cut-off separation.

Membranes are manufactured from different polymers, the most common of which are cellulose acetate, polysulfone, and aromatic polyamides. They are available commercially in different modular configurations, the most common of which are the hollow fine and spiral wound.

Each membrane type and configuration has inherent advantages and disadvantages which should be evaluated for major investments. Several international suppliers offer proven commercial applications for the reclamation of raw sewage and secondary effluents. Removal of larger than 8 for E.coli from feed containing 1.0 E.coli + 8 per 100 ml can be achieved by several MF and UF products (19, 20).

UF and MF have proven to be reliable and efficient for producing high quality drinking water and for processing industrial water from wastewater or surface water. The primary benefits of this technology are reliability, low operating cost and minimum environmental impact.

E. QUALITY CONTROL OF TREATED WASTEWATER

The health aspects of wastewater treatment as well as the practical applications of the reclaimed water are of primary importance in water reuse. Quality control is essential for any water reclaimed from polluted sources. Monitoring and control activities are necessary at the source of major pollutants, especially at the discharge points of some industries as well as at the intake and outlet of wastewater treatment plants, since in many cases the only method of providing effluent for safe reuse is to prevent the discharge of toxic materials at the source.

Surveillance and control of operations at the treatment plants must be thorough and comprehensive in order to identify the constituents of the pollutants in wastewater, determine if public health and technical criteria are being met and ensure effective use of the facility.

The types of examinations needed at the treatment plants are outlined below; details can be found in any standard wastewater treatment textbook.

(1) Biological examination: irrespective of the proposed reuse of the reclaimed water, samples should be taken for microscopic examination to detect the presence of protozoan cysts and parasite eggs;

(2) Detection and monitoring of bacteria: immediate bacterial counts in samples should be made directly after treatment to assess the overall performance of treatment and disinfection processes;

(3) Virus detection: examination for enteric viruses is very important if the reclaimed water is to be used for any domestic or municipal purpose where human contact is unavoidable. It is not practicable to examine water for viruses as frequently as for bacteria; seven days are required to carry out virus tests, which require suitable laboratories. However, viruses do not multiply outside host cells; therefore, the samples may be transported to a central laboratory for examination without affecting the sample;

(4) Chemical testing: The chemical testing programme is determined by the quality requirements of the water reuse application, and the range of required tests is presented in table 10 for various uses.

Generally, BOD and TSS contents are taken as indicative of the quality of the purified wastewater, with occasional testing of the other qualities; this is the current practice in the Middle East. BOD and SS are good indicators of the quality of effluent for a treatment plant which has been well designed to produce the desired qualities and is operating properly, especially for irrigation and landscaping purposes. However, if the effluent is to be used for industrial and municipal purposes a well-equipped laboratory is necessary to monitor the quality.

Sampling frequency for analysis of water samples depends upon the quality conditions, the economical and ecological importance of the water, the quality changes during the year, and technical-economics possibilities. Reliable automatic measurements can be made of pH, conductivity (salinity), turbidity, dissolved oxygen, and temperature. Sampling for other constituents may be made in frequencies ranging from daily to monthly. Overall examination of the treatment plant should be carried out several times a year, as necessary.

F. DISPOSAL OF WASTES, SLUDGES AND RESIDUES

The disposal of sewage or partially treated effluent by spreading it on the land is one of the earliest methods of sewage disposal. However, the health hazards for the workers on the land and the consumers of crops raised on such land may be considerable; for this reason it is not a recommended method of disposal.

The treatment of municipal and industrial wastewater always involves removal of sludges, slurries, and brines which create disposal problems, accounting for a considerable portion of the total treatment costs. Many towns incinerate municipal waste sludge after additional processes, but most sludges are disposed of either by spreading them on the land or by burial in selected locations. Sludge which is produced as a by-product of most treatment processes has considerable potential as a soil conditioner and fertilizer, and in many places it is discharged directly onto agricultural land in liquid form as an economical means of disposal. Organic matter is normally considered to be a nutrient in soils because of its influence on soil structure, its water-holding capacity, water penetrability, action exchange capacity and absorption of heavy metals. However, sludge with a significant industrial content may contain compounds which are damaging to the soil and regular monitoring of soil conditions becomes essential. In some places the sludge is dewatered before it is transported to be spread on land. However, the value of dried sludge as a conditioner is less than the value of sludge in liquid form and some wastes, particularly those containing nonferrous metals, may render the sludge toxic to plants.

The least desirable substances tend to be concentrated in sludges. Bacteria, viruses, cysts and parasite eggs are all found in raw municipal sludges, and to a lesser extent in digested sludges. Toxic substances and heavy metals are found in much higher concentrations in industrial sludges than in the wastewater from which they were extracted. Industries that produce large quantities of sludge will usually develop their own methods of disposal. Others that discharge their effluent to the city sewage system complicate the disposal problem. In processes that employ membrane separation, brines with high concentrations of minerals are produced as by-products. Disposal of such residues is usually handled by burial at locations that would not contaminate the groundwater.

Table 11 presents various methods for the ultimate disposal of concentrated contaminants resulting from advanced wastewater treatment.

Liquid sludge is valuable for both its water content and the nutrients it contains. Although land disposal appears to be the most viable way of disposal, guidelines for this practice are very scarce. In some places sludges are subjected to heat treatment in order to kill any remaining pathogens before agricultural use is permitted. In any event sludge must not come into direct contact with fruits or vegetables that will be eaten without cooking or peeling.

TABLE 10. IMPORTANT CONSIDERATIONS IN SELECTION AND EVALUATION OF ADVANCED WASTEWATER TREATMENT UNIT PROCESSES

Factors	Remarks
Process applicability	The applicability of a process is evaluated on the basis of past experience, data from full-scale plants and pilot data from plant studies. If new or unusual conditions are encountered, pilot-plant studies are necessary.
Applicable flow range	The process should be matched to the expected flow range. For example, stabilization ponds are not suitable for extremely large flows.
Applicable flow variation	Most unit operations and processes work best with a constant flow rate, although some variation can be tolerated. If the flow variation is too great, flow equalization may be necessary.
Influent wastewater characteristics	The characteristics of the influent affect the types of processes to be used (e.g., chemical or biological) and the requirements for their proper operation.
Inhibiting and unaffected constituents	What constituents are present that may be inhibitory, and under what conditions? What constituents are not affected during treatment?
Climatic constraints	Temperature affects the rate of reaction of most chemical and biological processes. Freezing conditions may affect the physical operation of the facilities.
Reaction kinetics reactor selection	Reactor sizing is based on the governing reaction kinetics. Data for kinetic expressions are usually derived from experience, the literature, and the results of pilot-plant studies.
Performance	Performance is most often measured in terms of effluent quality, which must be consistent with the given effluent-discharge requirements.
Treatment residuals	The types and amounts of solid, liquid and gaseous residuals produced must be known or estimated. Often, pilot-plant studies are used to identify residuals properly.
Sludge-handling constraints	Are there any constraints that would make sludge handling expensive or unfeasible? In many cases, a treatment method should be selected only after the sludge processing and handling options have been explored.
Environmental constraints	Nutrient requirements must be considered for biological treatment processes. Environmental factors, such as the prevailing winds and wind directions, may restrict the use of certain processes, especially where odours may be produced.

TABLE 10. *(continued)*

Factors	Remarks
Chemical requirements	Depend on water sources and type of processes.
Energy requirements	The energy requirements, as well as probable future energy costs, must be known if cost-effective treatment systems are to be designed.
Other resource requirements	Depend on additional resources committed to the successful implementation of the proposed treatment system using the unit operation or process in question.
Reliability	Depends on the long-term record of the reliability of the unit operation or process under consideration, its ability to stand periodic shock loading, and the manner in which such occurrences affect the quality of the effluent.
Complexity	The complexity of the process to operate under routine conditions and under emergency conditions such as shock loadings, as well as the level of training of the operator.
Compatibility	Can the unit operation or process be used successfully with existing facilities? Can plant expansion be accomplished easily? Can the type of reactor be modified?

Another method of disposal on land is to compost sewage sludges with municipal solid waste beforehand. In such cases it is advantageous to have the wastewater treatment plant and the composting plant at the same location.

Sludge can be transported by pipelines, especially designed trucks, barges or railway cars; the actual costs depend materially on the conditions peculiar to each problem.

TABLE 11. DISPOSAL METHODS FOR CONCENTRATED CONTAMINANTS REMAINING FROM ADVANCED WASTEWATER TREATMENT

Disposal method	Remarks
Liquids:	
Evaporation ponds	Provisions must be made to prevent groundwater contamination.
Land application	Provisions must be made to prevent groundwater contamination.
Shallow-well injection	Provisions must be made to prevent groundwater contamination.
Deep-well injection	Porous strata and natural or artificial cavities should be available.
Landfill	Liquid can be used as a wetting agent to increase compaction.
Controlled evaporation	Applicability depends on liquid power costs and local conditions.
Ocean discharge	Transportation by truck, rail, or pipeline is required. Ocean discharge will not be allowed in the future.
Sludge:	
Land application	Sludge may be pretreated to aid dewatering or to remove objectionable components.
Lagooning	Provisions must be made to prevent groundwater contamination.
Landfill	Sludge can be used as a wetting agent to increase compaction.

TABLE 11. *(continued)*

Disposal method	Remarks
Recovery of products	Recovery depends on sludge characteristics, recovery technology and costs.
Wet combustion	Heat value may be recovered for use. Disposal of ash is required.
Incineration	Concentration of sludge and disposal of ash is required.
Ash:	
Landfill	Ash can be mixed with solid wastes to increase compacted density of landfill.
Soil conditioner	Applicability depends on waste characteristics.

VI. THE ECONOMICS OF WASTEWATER REUSE

The decision to use reclaimed wastewater should take into consideration a number of factors, including the availability, reliability and cost of development of conventional ground and surface water sources. Other concerns include the cost of rainwater harvesting, the availability of brackish or sea water and the cost of desalination. It is also necessary to evaluate the practicability and costs of weather modification and other water augmentation techniques. If water of desired quality can be supplied by the other methods at costs less than that for water obtained from advanced treatment of secondary effluent, then advanced treatment facilities should not be built for water reuse. Furthermore, since the purified effluent is not to be used for drinking and its use is limited to certain purposes, the cost of treatment will vary according to the purification processes required to meet certain quality levels required by the users. However, the treatment costs are usually not more than a quarter of the total cost of the system.

A. UNIT COST OF RECLAIMED WATER

Costs in 1980 dollars reflect a minimum of $0.13 and an average of $0.27 per cubic metre. In South Africa, where the effluent is treated up to drinking standards and forms about one third of the potable water supply, the cost is similarly estimated to be $0.31 per cubic metre. It can therefore be assumed that the cost of complete advanced treatment of municipal wastewater for reuse is below $0.40 per cubic metre. This is a very favourable unit cost compared with that of desalting sea water, although the latter produces a product of drinking water quality. In general, reclamation of wastewater for reuse should be considered when it is not to be used for potable, domestic or close contact purposes.

Techniques such as desalination produce fresh water at lower costs than distillation, especially if brackish water is available instead of sea water. Notably, the reverse osmosis process produces supplies of fresh water at 25 per cent of the cost of distillation and becomes competitive with the purification of effluent when unlimited supplies of brackish water are available. In such a comparison, if there are existing facilities for treatment of wastewater to prevent pollution, only the additional cost of the advanced treatment process and the cost difference between supply systems need to be considered. If there are no existing facilities, then a cost element covering these facilities must be included in the financial analysis. Although a wastewater treatment plant reduces hazards to health and improves the amenities of life, it is difficult to establish its value and necessity as a utility, especially in the developing countries.

In the economic analysis of a water reuse project, it might be necessary to relate the short-, mid- and long-term prices of water conservation and reuse strategies to such costs as supply, interest rates and operation and maintenance in order to derive the average cost or the 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 present value of future benefits and costs, in addition to the present costs. In order to perform a reliable analysis, required data include information on appropriate costs, benefits, and discount and inflation rates, and such technical information as performance characteristics, energy requirements, reliability and project duration. 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 the Gulf countries, there is a national desire to develop and maintain public green areas for amenity purposes. Where this type of utilization is adopted as the sole use, the benefits are not tangible, and it is difficult to attempt a complete economic analysis.

The factors that govern the economics of water reuse include the size of the treatment plant, the composition of the wastewater, the required quality of the finished water, the location of the plant and the cost of alternatives. Usually the major costs in an effluent reclamation scheme arise from the distribution system, plant structure and interest on borrowed money. Only about a quarter of the total cost can be attributed to the actual cost of treatment. In a major water reuse project in Dubai, financed by the Government of the United Arab Emirates, the total cost of items involving effluent purification processes, from inlet works through tertiary treatment, was 233.4 million UAE dirhams ($64 million) and constituted 0.27 per cent of the total overall scheme cost. The total transport costs, 425.0 million UAE dirhams ($115.4 million), were almost double this amount and made up almost half the total project cost. They included sewage collection system costs as well as the distribution costs of the treated effluent which had to be transported to the points where it could be reused or integrated into the users' supplies.

In an economic analysis for this project, money market rates had to be considered in order to make cost estimates for the purified effluent. Since interest rates fluctuate continuously and a definite assessment of the project's life could not be made, capital recovery costs were estimated for project life periods of 20, 30, 40 and 50 years at various amortization rates. These costs varied between $0.35 and $0.52 per cubic metre of purified effluent and were still competitive with sea-water distillation costs. Table 12 provides a comparison of these estimates with costs elsewhere, showing that the cost of effluent purified by advanced treatment processes appeared to vary between $0.15 and $0.35 per cubic metre in the same year (1981) at various locations in California. The higher unit cost in Dubai may be attributed to the heavy transport component of the project. Where the topography is suitable, product transport costs can be eliminated by locating the treatment plant near a stream and discharging the purified effluent into the water course for abstraction downstream, which may lower overall costs appreciably.

In Kuwait, the total cost of a complete tertiary level treatment plant, together with its distribution system and appurtenant structure costs, was estimated to be 110 million pounds sterling ($225.5 million) in 1980/81. This plant was expected to produce a total of 342,500 cubic metres per day for use in 2,500 hectares of intensive agriculture and 9,000 hectares of environmental forestry. Assuming the same capital recovery and operation and maintenance cost rates as in Dubai, the unit cost of treated effluent was estimated to vary between $0.18 and $0.31 per cubic metre.

It was expected that in the earlier years of operation the actual unit cost of purified water would be higher, since full capacity would not be reached until the population rose to the level designed for and the plant produced the complete project design volume totals. Nevertheless, all the above exercises indicate that water purification can be competitive as an alternative non-conventional source in areas with very limited water resources.

B. WASTEWATER RECLAMATION COSTS AT DIFFERENT TREATMENT LEVELS

Although some of the components of wastewater reclamation projects are similar, including infrastructure, influent and effluent systems, and site works, the cost of treatment systems and related works is proportional to the degree of treatment required. If the effluent is being purified for industrial reuse, treatment should be provided to meet the water quality criteria demanded by the industries involved. As mentioned above not all industries would require wastewater to be treated up to the quality of the municipal supply.

Generally, industrial reuse of wastewater has two significant advantages over agricultural reuse: first, the location of use is usually closer to the supply of wastewater and the needs are generally continuous, on a 24-hour-a-day and 365-days-a-year basis, whereas agricultural use is both scattered and seasonally distributed; second, many industrial water quality requirements can be met by secondary-treated wastewater or by adding a few processes to existing secondary facilities. In fact, industrial quality requirements may vary depending upon the particular requirements of each industry and, therefore, the determination of reuse potentials for specific industrial applications normally requires detailed study on a case-by-case basis.

TABLE 12. UNIT COST ESTIMATES FOR ADVANCED-TREATED EFFLUENT AT VARIOUS LOCATIONS IN CALIFORNIA

Location	Plant size (m^3/d)	Unit cost ($/$m^3$)
South Tahoe, California	28 400	0.35
Santa Clara Valley Water Department	1 510	0.15

TABLE 12. (*continued*)

Location	Plant size (m^3/d)	Unit cost ($/$m^3$)
Los Angeles County Sanitation Department	..	0.16
Water Factory 21 (Orange County, California)	56 775	0.24

Source: J.G. Milliken, and D.C. Taylor, "Metropolitan water management", *ACU Water Resources Monograph 6* (Washington, D.C., 1981), p. 110.

Note: .. Data not available.

Table 13 presents the overall average treatment costs in the United States for different treatment levels. Advanced wastewater treatment plus the reverse osmosis process usually yield purified effluents at drinking water standards and the costs, compared with those of other treatment levels, are considerably higher. The costs are for the complete treatment, from untreated wastewater through the treatment processes shown.

Land treatment costs, especially for groundwater recharge, are usually lower than those for mechanical methods of purification. For surface spreading and recharge by rapid infiltration, the required pre-application treatment is usually primary or secondary treatment. The capital costs of rapid infiltration for a system that treats 3,785 cubic metres per day, using a facultative pond for pre-application, were estimated at $0.20 per cubic metre in the United States, including the cost of 8.1 hectares of land for surface spreading at a cost of about $12,380 per hectare (at March 1980 costs). Operation and maintenance costs were estimated to vary between $0.02 and $0.03 per cubic metre (same year). However, the capital costs may differ considerably with the prevailing value of land. Capital costs of slow rate systems were estimated to be about $0.22 per cubic metre with operation and maintenance costs at $0.05 per cubic metre for a new plant of 3,785 cubic metres per day capacity. Land costs made up about 25 per cent of the capital costs (1980 levels). Considering that evaporation rates may be considerable in dry and hot climates, the losses may be significant and thus the system would yield lower volumes of water. Therefore, the slow rate type of land treatment may not be attractive in and areas with high land costs.

Overall, primary, secondary and some tertiary levels of wastewater treatment are associated with conventional municipal sewage plants, which are fairly standard in design and construction. Physical removal of settleable and floating solids from the wastewater by inlet works and mechanical means in primary treatment usually involves only a very small percentage of the total cost of the system (in the Dubai plant, 5 per cent), and operation and maintenance are fairly straightforward. Secondary treatment costs and the tertiary (advanced treatment) costs are much higher depending on the unit processes necessary for treating the effluent to required quality levels. Running costs depend upon the energy requirements as well as the maintenance and administrative costs.

C. WASTEWATER TREATMENT COSTS BY DIFFERENT PROCESSES

Since the kind of treatment wastewater must receive prior to reuse depends upon what its ultimate use will be, various treatment processes available today were briefly described in earlier sections of this study. Existing sewage plants around the world represent investments that cannot, from an economic point of view, be abandoned, since they provide a significant part of a total process of removal of contaminants. However, in order to bring the final product up to usable standards, additional treatment processes are required. According to the quality of the available primary or secondary-treated effluent and the levels required, one or more advanced treatment processes may be selected. New plants for production of purified wastewater for reuse would require a train of these processes, together with a suitable combination of primary and secondary removal stages.

TABLE 13. UNIT COST FOR WASTEWATER RECLAMATION AT DIFFERENT TREATMENT LEVELS

Treatment system (37,850 m^3/d plant capacity)	Unit cost* ($/$m^3$)
Activated sludge (secondary)	0.16
Secondary plus filtration	0.19
Secondary plus activated carbon	0.25
Advanced wastewater treatment plus reverse osmosis	0.75

Source: R.W. Crites, "Economic of reuse", *Proceedings of the Water Reuse Symposium II* (Washington, D.C., 1981).

Note: * Based on costs for October 1980.

Removal efficiencies of various advanced treatment processes for different contaminants in wastewater were discussed in detail above. The types of contaminants found in municipal sewers are more or less similar everywhere, despite variations in the concentrations and individual contaminants. This similarity has lead to the development of generalized advanced methods that can be widely applicable in advanced treatment.

Table 14 presents various processes and their functional purposes together with corresponding removal efficiencies and costs. The cost figures presented here may be out of date and not applicable everywhere and should not be taken as a basis for any economical analysis. They were included here in order to illustrate the relative costs of different treatment processes. In selecting a process, technical feasibility of a particular method, as well as its economic viability, should be investigated, and its applicability under prevailing local conditions should be considered.

D. ENERGY REQUIREMENTS FOR WASTEWATER RECLAMATION

The energy required to supply treated water for a particular use is dependent upon the quality necessary for use, the difference in the head, the distance from the source to the use site and the mode of conveyance of the water. In the evaluation of a proposed water reuse project, the overall energy requirements must be considered. However, this may be difficult for a number of reasons.

First, the total energy requirement of a particular reuse alternative is highly site-specific and is influenced by the community wastewater system. A particular treatment plant for reuse may not result in energy savings at one location but may be efficient at another location owing to, among other factors, varying pumping costs, construction and maintenance of the system, the availability and quality of effluent supplies, and the cost of manufacture and delivery of treatment chemicals and system replacement equipment, such as pumps and pipes. Pumping costs are dependent upon the type of pump, the change in head, and the pumping distance through the inflow and outflow system.

The quality of water to be used in the system is another important factor, since lower quality influent requires more energy for purification to meet certain specific standards. Wastewater treatment is a major energy use factor in the system. Table 15 presents specific energy requirements for removal of constituents from wastewater by different processes.

The actual and projected prices of energy have varied greatly in recent years, thus complicating any cost estimates or economic analysis that may be attempted involving projected energy costs. Furthermore, subsidies may hide the true energy cost of an existing or planned system. Therefore, no energy cost is presented in this study. In the past, owing to the low cost and abundance of energy, little consideration was given to its usage in the planning and design of water purification systems. However, in recent years energy-related costs have become increasingly important.

Generally, advanced treatment systems are the most energy-intensive, and land treatment methods are the least expensive. Energy needs for land treatment systems consist of pre-application treatment;

transmission to the application site, if necessary; distribution pumping; and drainage pumping. Again, the energy required for pre-application treatment varies considerably depending on the type of system, site conditions, and regulatory requirements. Energy transmission from the pre-application treatment site to the land treatment site depends on topography and distance. For sites located below the pre-application treatment facilities, pumping is normally not required.

Slow rate systems vary in terms of distribution energy and possible tailwater control. Rapid infiltration systems are usually designed for surface distribution and application and therefore require minimal energy. Some pumping may be needed to control groundwater levels. Overland flow systems can use surface distribution with low head requirements.

Table 16 presents the specific energy requirements for various secondary treatment processes. Table 17 presents average thermal efficiencies and heat contents of various energy sources.

The typical forms of energy utilized in wastewater treatment are coal, petroleum products, natural gas and electricity. The efficiencies and cost per unit of energy delivered from these sources vary significantly. Owing to limited availability of data and significant differences in the cost of energy sources, all the requirements have so far been presented without the unit costs. However, in an economic analysis the financial implications of various treatment trains and systems should be analysed after the relevant cost structures of energy alternatives are clearly established.

Wastewater reuse in the ESCWA region is increasing, as the cost of production of fresh water is reaching very high figures. As pointed out above, one cubic metre of treated wastewater ready for reuse for purposes other than drinking costs approximately $0.40. This is a very feasible figure compared to the cost of desalination, and treated wastewater may have numerous applications in industry and agriculture not requiring very high quality water.

TABLE 14. COMPARISON OF EFFICIENCIES AND COSTS OF WASTEWATER RECLAMATION PROCESSES

Process description	Treatment provided (Substance removed)	Removal efficiency (Percentage)	Type of waste	Unit cost ($/m^3)
Secondary treatment (raw sewage)	Suspended solids organic matter	90 SS 90 BOD	Sludge	0.80-3.2
Anaerobic denitrification (irrigation wastewater)	Nitrate-nitrogen	80-95	None	0.52-0.80
Algae harvesting (irrigation wastewater)	Nitrate-nitrogen	50-90	Algae	0.52-1.1
Ammonia stripping (raw sewage)	Ammonia-nitrogen	90-95	–	0.26-0.80
Ion exchange (filter effluent)	Nitrogen-phosphorus	80-98	Liquid	4.50-6.60
Electrodialysis (carbon filter effluent)	Dissolved solids	10-40	Liquid	6.60-20.00
Chemical precipitation (as effluent)	Phosphorus	88-95	Sludge	1.1-2.10
Carbon adsorption (A/S or sand filter effluent)	Organic material	90-98	Liquid	1.1-2.10

TABLE 14. (*continued*)

Process description	Treatment provided (Substance removed)	Removal efficiency (Percentage)	Type of waste	Unit cost ($/m^3)
Filtration (A/S effluent)	Suspended solids	50-90	Liquid and sludge	2.26-0.80
Reverse osmosis (carbon filter effluent)	Dissolved solids	65-95	Liquid	2.20-10.40
Distillation (carbon filter effluent)	Dissolved solids	90-98	Liquid	0.40-40.00
Foam separation (A/S effluent)	ABS	–	Liquid	0.26-0.52

Source: Adapted from E.J. Middlebrooks, *Water Reuse*, (Ann Arbor, Michigan, 1982).

Notes: A/S Activated sludge.
– Not applicable.

TABLE 15. SUMMARY OF SPECIFIC ENERGY REQUIREMENTS FOR REMOVAL OF CONSTITUENTS FROM WASTEWATER BY DIFFERENT ADVANCED TREATMENT PROCESSES

Removal	Process	Total energy requirement		
		Electr. Kwh/kg	Fuel BTU/kg	Combined BTU/kg
Nitrogen	Nitrification, single stage	6.8	15.9	88.1
(In the form of NH_3-N	Nitrification, two stage	9.0	15.9	110.1
or NH_3-N or NO_3-N)	Denitrification, suspended growth	2.6	11.7	39.7
	Denitrification, biofilm	1.1	11.7	24.2
	Ammonia stripping (18°C-24°C)	15.9	–	167.4
	Ammonia stripping (13°C)	30.8	–	323.8
	Selective ion exchange	17.2	12775.0	12 951.5
Phosphorus	Alum	2.0	52.9	73.8
(Based on removal of	Lime	15.9	34.4	200.9
10 mg/l alkalinity)	Lime recalcination	52.9	2.6	447.3
	Ferric chloride	13.0	–	136.6
	Phostrip	2.6	57.9	85.7
	A/O process	1.3	–	13.7
Refractory organics	Granular carbon regeneration	1.3	4.4	18.3
(Based on removal of:	Powdered activated carbon	0.03	13.2	13.7
*40 mg/l COD 450	Powdered carbon regeneration	1.5	6.2	22.5
mg/l COD)	Fluidized bed	1.5	26.2	42.5
	Wet air oxidation	0.33	--	3.5
	Ozone oxidation*	17.6	–	185.0
	Reverse osmosis	1.8	--	18.5
Total dissolved solids	Electrodialysis	1.3	--	13.9
(Based on removal of	Ion exchange	0.01	46.3	46.3
1 000 mg/l TDS)	SANAX	0.04	21.6	22.0
Disinfection	Chlorine, 5 mg/l	0.023		243.0
	Chlorine dioxide, 5 mg/l	0.083		875.0
	Ozonation, 5 mg/l	0.106		1 110.0
	Ultraviolet (3 785m^3/day plant)	0.042		444.0

TABLE 15. *(continued)*

Removal	Process	Total energy requirement		
		Electr. Kwh/kg	Fuel BTU/kg	Combined BTU/kg
PH adjustment	Recarbonation			766.0
	Liquid CO_2			608.0
	Stack gas			5 892.0
	Gas burner			555.0
	Sulfuric acid			5 284.0
	Sodium hydroxide			9 775.0
	Lime			
Dechlorination	Sulfur dioxide	0.7	–	7.1
(Plant size 3 785m^3 per day)	Activated carbon (based on 1.20m head loss)	0.9	136.6	145.1

Source: Adapted from W.F. Owen, *Energy in Wastewater Treatment* (New Jersey, Prentice-Hall, 1982).

Notes: – Not applicable.
-- Negligible.
A/O Acrated oxygen.

TABLE 16. SUMMARY OF SPECIFIC ENERGY REQUIREMENTS FOR SECONDARY TREATMENT PROCESSES

Process	Typical application	Specific stabilization energy (Kwh/kg BODL)
Conventional activated sludge	Polishing, all sizes of plant	0.86-2.42
High purity oxygen activated sludge	Polishing, large plants	0.88-1.17
Oxidation ditch/extended aeration	Polishing, small plants	1.50-3.30
Trickling filter/RBCs	Roughing or polishing, all sizes	1.53-1.32
Aerobic lagoon	Roughing	6.83-17.18
	Roughing	1.98-3.30

Source: Adapted from W.F. Owen, *Energy in Wastewater Treatment* (New Jersey, Prentice-Hall, 1982).

Notes: BODL Ultimate BOD.
RBC Rotating biological contact.

TABLE 17. AVERAGE THERMAL EFFICIENCIES AND HEAT CONTENTS OF VARIOUS ENERGY SOURCES DELIVERED TO THE CONSUMER

Energy source	Delivered values	
	Heat content	Efficiency of energy delivered to consumer (Percentage)
Coal (Bituminous lignite)	24 200 BTU/kg	93
Petroleum	36 500 BTU/litre	93
Natural gas	36 300 BTU/m^3	93
Electricity	3 412 BTU/Kwh	25

Source: Adapted from W.F. Owen, *Energy in Wastewater Treatment*, (New Jersey, Practice-Hall, 1982).

VII. ENVIRONMENTAL AND PUBLIC HEALTH CONSIDERATIONS IN WASTEWATER REUSE

The most critical consideration in the use of treated wastewater is that of health. The reclaimed water must be both treated and used in such a way that the contaminants it may contain will not be a danger to human beings and to other living species. Most of the known pollutants in sewer effluent can be eradicated by present treatment techniques; however, some contaminants cannot be totally removed and may have short as well as long-term effects. Risks to human and animal life can occur as a result of deliberate or accidental drinking of improperly treated effluents, coming into bodily contact with them, inhaling aerosols containing the pathogens, and consuming fruits or vegetables, or grass and fodder in the case of animals, that have been in recent contact with the effluent. Wastewater can be hazardous to health owing to the presence of toxic chemicals and pathogens that cause infectious diseases.

A. TOXIC CHEMICALS

There is increasing concern about the presence of chemical agents in wastewater. The present report does not recommend the use of treated effluents for potable purposes. Nevertheless, health risks associated with potential toxicity should be assessed for wastewater reuse projects, especially where the crops or products are to be consumed by human beings or animals, although in most cases toxicity to crops is likely to occur before there is significant risk to public health. The chemicals are more often associated with chronic or long-term effects rather than with acute symptoms.

Toxic chemicals added to soils by irrigation with treated wastewater are not a hazard to the food chain unless they have entered an edible part of a plant, or unless animals graze on sites treated with reclaimed water. Elements with a significant potential hazard to the food chain through accumulation in plants are cadmium (Cd), copper (Cu) and zinc (Zn). Plants containing excessive Zn levels are usually severely injured and show economically damaging reductions in yield. Zn is also toxic to some sensitive animals. However, the food chain appears to be protected since yield is usually reduced at lower plant Zn levels than those that injure the animal that consumes the plant. Cd, similar to Zn, increases in soil through effluent application and can lead to increased food-chain Cd. In some countries there are permissible levels of Cd in foods in the market, and it appears that the only way to prevent Cd from being accumulated to levels that can be a potential hazard in the food chain is to reduce the Cd content of sludges to 0.5 per cent of the Zn content (and as near as possible to 0.1 per cent of the Zn content). Cu will cause severe plant injury before the content is high enough to be toxic to most animals. However, sheep are found to be very sensitive to plant Cu, and forages grown on soils enriched in Cu by effluent treatment may form a hazard until the Cu is washed away by rain. If high amounts of chromium (Cr) ion are added to the soil, the Cr content of crops does not increase appreciably and constitutes no hazard. Boron (B), cobalt (Co) and nickel (Ni) at levels that severely injure the plant present no threat to the food chain. Mercury (Hg) does not appear to constitute a food chain accumulator in agriculture; lead (Pb) is not translocated readily to plant tops and is excluded from grain, fruits and edible roots.

Toxic chemicals may pose a direct threat to human health if they reach the aquifers during land treatment or irrigation application. Their levels may be diluted in groundwater; however, continuous monitoring would be required to prevent a build-up, especially in aquifers from which drinking water is drawn. Similarly, toxic elements washed into streams from soils treated with wastewater may pose danger downstream where the runoff is abstracted for various uses. However, in many parts of the world the existing surface water supplies are already somewhat contaminated with municipal and industrial wastes; therefore, runoff from wastewater-treated fields may not make a difference.

In addition to toxic chemicals, excessive quantities of such common chemicals as nitrogen, lead and sodium have significant effects on health. Finally, there is an increasing spectrum of complex chemical compounds which are suspected of causing cancers. Thus, if industrial wastewaters are included in the effluent being treated, it is likely that there will be a wide range of chemicals to be concerned about.

B. PATHOGENIC ORGANISMS

As mentioned above, the major pathogens present in domestic sewage are bacteria, viruses, protozoa and helminths. Infectious diseases caused by biological agents in wastewater can be classified according to the type of pathogen (bacterial, viral, parasitical), the site of infection (enteric, respiratory, dermal), or the primary mode of transmission (foodborne, airborne). Enteric diseases are usually transmitted by wastewaters, since the pathogens exit the body with traces. Other groups of diseases affecting the eyes, ears, nose, throat and skin may also be related to wastewater. However, considering the greater number of microbial species, only a few are typically pathogenic to man.

The most important diseases caused by bacteria and conveyed in municipal wastewater are cholera, typhoid, paratyphoid, bacillary dysentery, diarrhoea, enteritis, salmonella and other less serious diseases. Viruses are known to cause a variety of diseases, including infections, infectious hepatitis, poliomyelitis, enteric diseases and some eye and respiratory infections. Normally, the viral content of wastewater is much lower than the bacterial content, but as viruses are more resistant to treatment processes, their removal is achieved to a lesser degree, and disinfection is more difficult. Adequate disinfection by chlorination is highly effective in eliminating bacteria, but not as effective in removing viruses. Although the protozoan cysts that cause amoebic dysentery and enteric disorders are usually removed from the effluent by proper tertiary treatment, they remain in the sludge. Helminths, parasites that are present in municipal effluent, typically cause such diseases as bilharzia (schistosomiasis), ascariasis, and tapeworm and hookworm infections, which are usually transmitted through their eggs. A combination of sedimentation and tertiary treatment usually removes the eggs of these parasites. Ascarid eggs remain in the sludge and can be killed by heating.

Irrigation with untreated or improperly treated sewage effluent in direct contact with consumption crops presents high health risks. Even crops that are not consumed uncooked are still unsafe, since they may introduce pathogens into the kitchen, where working surfaces and utensils may become contaminated. Although the pathogens do not penetrate healthy, undamaged surfaces of vegetables and perish rapidly when exposed to sunlight on crop surfaces, they can survive for long periods inside leafy vegetables or in protected cracks in the stem. In order to safeguard public health, the effluent has to be properly treated before irrigation application, or its use should be restricted only to certain crops to ensure that improperly treated wastewater will not come into contact with any part of a plant used for human consumption. Furthermore, irrigation of fodder crops with such effluent poses a risk that cattle will be infected with the eggs or larvae of the beef tapeworm (taenia saginata) and other parasites that can be passed on to human beings when they eat such infected beef.

Special attention needs to be paid to the potential risks to agricultural workers on wastewater irrigation projects and to the people who live in adjacent residential areas. Direct contact with improperly treated wastewater by barefoot workers or contamination of their hands is hazardous. Helminths, in particular, present a risk for barefoot workers, causing hookworm and other enteric infections. Therefore, sanitary washing and eating facilities for workers and the promotion of good personal hygiene are necessary to reduce risks. Regular monitoring of the health of farm workers, developing a safety code, and continuing health education programmes are also useful. Another potential risk is inhalation of or contact with aerosolized effluent containing pathogens from spray irrigation or watering with hoses. Ingesting food or water on which aerosols have settled also leads to problems. People residing near treatment plants or employees working in such plants are subjected to aerosols as well. However, so far no correlation has been found to exist between human exposure to aerosols and the incidence of illness at or near treatment plants. Furthermore, it is not an easy task to assess the effects on public health of using treated effluent in irrigation. Nevertheless, it is a possibility that in hot and dry areas where the topsoil dries out easily, after irrigation with improperly treated effluent the highly resistant parasite eggs may be transported in the air with soil particles and may be inhaled by farm workers or nearby residents, or may be ingested with crops that the aerosols may settle on.

The use of improperly treated wastewater in fish ponds may also present some health hazards. There is the danger of bilharzia (schistosomiasis) transmission to pond workers through the snails that are often found in fish ponds. These snails should be controlled whether or not the fish ponds contain treated effluent.

The fish may not be biologically infected with human bacterial or viral pathogens, but they may carry these organisms into the kitchen on their external surfaces and viscera. Certain helminths capable of infecting fish may cause disease in man if the fish are eaten raw.

Recharging aquifers with improperly treated wastewater may cause groundwater contamination by the movement of bacteria and viruses into the aquifers. This is a situation that should not be allowed to occur at aquifers where the water is used for drinking purposes without further treatment. Such potential risks exist when the rapid infiltration type of land treatment is applied on coarse textured soils without allowing enough time for the removal of pathogenic organisms. Studies have indicated that elevated application rates of high virus concentrations on coarser soils can result in movement of the virus into the soil profile. However, a properly designed and managed system would prevent such occurrences.

The health risks involved in the use of reclaimed water for recreation purposes have not been fully evaluated. However, there is evidence that bathers in such waters can become infected with enteric diseases by involuntary ingestion of the water or by inhaling small water particles of aerosols. Thus, treated effluent should not be used for sports in which the effluent will come into contact with humans, and if there is no alternative source of water, only wastewater treated to the degree of meeting drinking water requirements should be considered.

C. OTHER HEALTH ASPECTS

In addition to the potential risks resulting from toxic chemicals and pathogenic organisms, aquatic insects can also present hazards to public health. The mosquito is one of the most important factors in the transmission of diseases, including malaria, encephalitis, and filariasis. The global war against the mosquito is continuing, but apparently without success, and this vector, although once on the decline, is currently making a comeback owing to widespread irrigation projects. In order to prevent the spread of such diseases, mosquito control is essential.

In order to reduce the health risks to consumers of crops produced from any agricultural development using purified effluent, tertiary treatment must be regularly monitored. In addition, the treated wastewater must be substantially free of all pathogens, and it should not be used on crops that are usually eaten raw and without peeling. The health of the farm workers as well as the irrigation techniques, irrigated solid characteristics and crop production should be under constant monitoring.

Reclaimed wastewater should not be used for potable purposes; distribution networks should be clearly marked in order to prevent the cross-connecting of pipelines carrying freshwater supplies and those transporting treated effluent. Leaks also should be prevented. The health of the farm workers should be regularly monitored. In order to prevent infections resulting from aerosol drift, as well as avoid other hazards to the people living nearby, farms and residential areas should be located at safe distances from each other.

Wherever treated wastewater is used, health agencies should establish standards and strict regulations 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 severe deterioration in the quality of the treated wastewater, continuous and safe operation should be secured, and if the end product does not meet the standards, it should not be released for use.

In the ESCWA region wastewater reuse has been practiced, though on a limited scale, over a number of decades. However, so far no epidemic or serious infections have been reported thanks to the limited use of the treated effluent and the safety precautions undertaken.

In Kuwait the policy related to treated wastewater restricts its use to the irrigation of forestry, fodder crops and certain horticultural products. The use of treated wastewater to irrigate public parks and gardens, or for municipal purposes such as fire-fighting and street cleaning, or for domestic purposes such as garden watering and toilet flushing, is not included in future planning for Kuwait.

On the other hand, in Qatar, some municipal areas of Doha have been irrigated with treated wastewater for nearly thirty years, without any noticeable hazardous effects on public health or on the environment. There are plans for expanding the present use of treated effluent for landscaping and other municipal purposes, eventually shifting the bulk of its use to agriculture.

Future projects elsewhere in the ESCWA region are planned, involving limited use of the treated effluent but with broader applications in various industries as well as for municipal and agricultural purposes. The standards to be met by the treated effluent reach those of drinking water, particularly in Saudi Arabia, and strict application of these requirements, in addition to careful practices in the field, should minimize any possible hazards to public health and the environment.

VIII. APPLICATIONS IN SELECTED ESCWA MEMBER COUNTRIES

The ESCWA region is considered the world leader in utilizing non-conventional sources of water, especially desalination. Over 65 per cent of the total installed capacity of all desalination plants in the world is located in the ESCWA region, primarily in the GCC countries. Table 18 lists by volume the renewable sources of water in the ESCWA member countries, from both conventional and non-conventional sources.

One of the first land-based seawater desalination plants in the world was commissioned in 1907 to provide drinking water to Jeddah (Saudi Arabia). It was replaced with two new units in 1928. Aden and Qusay'ir (Yemen) are other cities which have relied on seawater desalination for most of their potable water supply for more than 60 years. Kuwait was instrumental in developing the MSF process in the 1950s. In the 1960s, Saudi Arabia started its modern desalination programme, which has contributed tremendously to the country's economic progress and to the progress of desalination technology all over the world.

The importance of wastewater reuse was recognized in the ESCWA region a long time ago. Water reuse began in Qatar in the 1950s, followed by Kuwait, Saudi Arabia and the United Arab Emirates. Today, most of the countries of the region benefit extensively from both desalination and wastewater reuse.

A. BAHRAIN

In Bahrain overpumping of groundwater has increased its salinity. The Government has established that the maximum amount that can be supplied from the aquifer without affecting its quality is 67 MCM per year; the balance has to be supplied by desalination and reclaimed wastewater. The municipal demand satisfied from groundwater in 1996 was 44.7 MCM, while the total demand for the same year was 96.8 MCM. The balance was satisfied through desalination plants (27). Seawater desalination was introduced in Bahrain in 1976. As of 1996 the total installed capacity was located at three sites, as follows:

Sitra (MSF)	25 MGD
Ras Abou Jarjur (BRO)	10 MGD
Al-Dur (SWRO)	10 MGD

A new desalination plant (MSF, 30 MGD) is under construction at Al-Hidd and should be commissioned by 1999. An additional desalting capacity of 50 MGD will be required by the year 2005, according to the Government plan (m^3=220 gallons).

The Tubli wastewater plant is the major one in Bahrain. Its present capacity is 154,000 m^3/d (secondary treatment). Most of the effluent is discharged to the sea. For reuse in landscaping, about 25,000 to 30, 000 m^3/d are treated to tertiary standards using sand filtration, ozone and chlorination. Plans exist to increase the tertiary treatment capacity of the plant and construct pipelines and pumping stations. The expanded facility would take the reclaimed water to the west of Issa Town in order to irrigate 500 hectares in the agriculture area.

TABLE 18. RENEWABLE WATER RESOURCES IN ESCWA MEMBER COUNTRIES (1994)

	Renewable water resources MCM/year		
Country	Conventional	Desalination	Reuse
Bahrain	100.2	75	17.5
Egypt	59 600	31.7	4 790
Iraq	62 800	7.4	1 500
Jordan	953	2.5	61
Kuwait	160	388	30
Lebanon	3 100	1.7	2.0

TABLE 18. (*continued*)

Country	Renewable water resources MCM/year		
	Conventional	Desalination	Reuse
Oman	1 468	47.3	21.5
Qatar	50	131	33
Saudi Arabia	6 000	795	131
Syrian Arab Republic	21 475	2.0	1 447
United Arab Emirates	315	405	108
Yemen	4 900	9	52

Sources: J. Alalawi and M. Abdulrazzak, "Water in the Arabian peninsula: problems and perspectives", Cambridge, MA, Harvard University, 1993; Mohamed Hamoda, *Waste-water Treatment and Reuse in Agriculture* (Amman, IDB-WHO/CEHA Regional Workshop on Water Conservation and Reuse: Practical Approaches and Strategies, 4–7 March 1996); M. A. Mandil and Adil A. Bushnak, "Future needs of desalination in the Arab world", Abu Dhabi, IDA World Congress, 1995; Muwaffaq Saqqar, *Jordan National Experience: Waste-water Reuse* (Amman, IDB-WHO/CEHA Regional Workshop on Water Conservation and Reuse: Practical Approaches and Strategies, 4–7 March 1996); United Nations, Economic and Social Commission for Western Asia, *Water Desalination in Selected ESCWA Countries* (1995); Klaus Wangnick, *IDA Worldwide Desalting Plants Inventory No. 14* (International Desalination Association, 1996).

Note: Two dots (..) indicate that the information is not available.

B. EGYPT

The Government of Egypt commissioned a master plan and feasibility study for the Greater Cairo wastewater project in 1977, to be followed by the design phase, which is presently underway. The whole project comprises about 40 kilometres of rock tunneling for main and subsidiary sewers, related lift stations, conveyance culverts and force mains. Four sewage treatment works are each designed to provide full treatment for flows varying from 400,000 m^3/d to over 1,000,000 m^3/d, and sludge treatment facilities for 33,000 m^3/d of sludge. The project also has provisions for sewerage facilities for substantial residential areas on both banks of the river.

In the treatment works, primary treatment will be by sedimentation and secondary treatment by activated sludge. Tertiary treatment will be dependent on final use. Disinfection will be done by maturation or chlorination (and storage). The designed conductivity is up to 1,200 micromhos, and the BOD and TSS levels will be 5 mg/1 each.

The TSE will be employed in agriculture and aquaculture, and it is envisaged that it will be used initially to develop up to 40,000 feddans of land under irrigation. The system cannot be connected to the Nile irrigation system owing to a law passed in 1972 banning any discharge to that system.

The reuse of drainage water for irrigation purposes has long been in practice in Egypt. Records indicate that drainage water used for irrigation in both the Nile Delta and Upper Egypt is above 5 billion cubic metres, and the average annual total available drainage water is estimated to be between 14 and 16 billion cubic metres in the Delta. The amount of drainage water discharging to the Nile in Upper Egypt is about 2.3 billion cubic metres per year, and this amount is on the increase due to extension of the public drainage systems.

Drainage water is reused by direct pumping from the drains to the feeding canals, as well as by 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 throughout the year and, for the most part, 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 and Land Reclamation has been studying the possibility of using drainage water on soils with 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 for a large network of drainage canals and the branches of the Nile.

In addition an ongoing research project at the National Research Center is investigating the treatment requirements of heavy urban sewage for reuse in agriculture.

C. JORDAN

In the water resources Master Plan for Amman, it is planned that 10 MCM per year will be pumped from the King Talal Dam to assist in meeting the city's total water supply demand, reaching 50 MCM 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. There it will be mixed in the reservoir and will then be pumped back to Amman. Once in Amman, it will be purified to the required degree at a treatment plant for use again.

D. KUWAIT

Seawater desalination in Kuwait began in 1954 with a volume of 850,000 m^3/year. At present, there are five major desalination plants with a total capacity of 234 MGD. An additional plant with a capacity of 24 MGD is under construction.

The use of effluent in agricultural and forestry schemes has been practised in Kuwait for many years. Substantial amounts of septic tank contents are collected by tankers and used on government-controlled, enclosed afforestation areas where there is no public access. Although Kuwait has been able to develop slightly brackish water sources for irrigation of landscaping areas and private and public gardens, effluent is being increasingly used on restricted areas since the cost of brackish water and the 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 cubic metres per day available to the project, and irrigating alfalfa, winter forage crops, barley and a small amount of other 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 in 1970 the Food and Agriculture Organization of the United Nations (FAO) provided the State of Kuwait with a consultant on microbiology. The consultant investigated the nitrification of ammonium-N from sewage effluents after soil treatment, and the influence of sewage chlorination on nitrification processes, since the sewage effluents applied to vegetable crops should be chlorinated before use. In the report, dated 1972, the FAO consultant indicated that nitrifying bacteria, which transform ammonia into nitrites and nitrates during the summer months, were present and that the amount of chlorine remaining in the irrigation water should be as low as possible. At present, 30 million cubic metres of effluent a year are utilized, mostly from the Ardiyah treatment plant.

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 presently under construction, will produce 380,000 m^3/d of treated wastewater in three mainland and one island treatment plants. The civil engineering work on tertiary treatment elements for the effluent from the three mainland plants was completed in 1981. The primary and secondary treatment processes are sedimentation and activated sludge respectively. For tertiary treatment, the facilities provided are rapid gravity sand filtration with disinfection by chlorine before and after filtration. The quality of the wastewater will be BOD = 10 mg/l and TSS = 10 mg/l or better. The projected salinity level is about 2,800 micromhos. For fodder crops and forestry, the effluent standard is a coliform count below 1,000/100 ml, and for other crops, below 100/100 ml.

The distribution works include bulk transmission by pipeline, storage and distribution. The average and peak daily volumes of treated effluent are expected to be 0.4 and 0.68 million cubic metres respectively by the year 2010. The present policy in Kuwait restricts the utilization of treated effluent in irrigating forestry, fodder crops and certain horticultural products; therefore, uses for irrigating public parks, 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 the vegetables will be only those not eaten raw. The development of 2,500 hectares for agriculture and 9,328 hectares for forestry is planned by the year 2020, in various areas in Kuwait.

E. QATAR

Seawater desalination in Qatar began in 1953 with one plant producing 680 m^3/day. Today there are three major plants with a total capacity of 111 MGD.

Qatar has a long history of effluent reuse; some municipal areas of Doha have been irrigated with treated effluent since the 1950s. Presently, Doha has two wastewater treatment plants; Doha South treats 4,500 m^3/d tertiary treatment; and Doha West treats about 3,500 m^3/d of sewage transported by trucks from areas not served by collection network. About 67 per cent of the treated wastewater is used in the production of forage and the balance is used for landscaping. The key obstacle in utilizing reclaimed wastewater in Qatar is its high salinity from, 2,500 to 7,500 ppm.

F. SAUDI ARABIA

With very little rain and practically negligible surface water resources, Saudi Arabia is one of the driest areas of the world. In order to cope with its historical scarcity of water, the Government has taken steps to develop new sources of water supply as well as to recycle part of the present wastewater in some areas. The Saudi Government undertook a major programme to provide potable water for all major cities and coastal towns that have no conventional source of water. Table 19 lists the major seawater desalination plants in Saudi Arabia. Inland cities such as Riyadh, Mecca, Medina, Taif and Abha are supplied from these plants through trunk pipelines.

The total seawater desalination capacity of major government plants in 1997 was 720 MCM/year. An additional 80 MCM/year are produced by many smaller public and private seawater desalination plants. Four large desalination plants are under construction, which should increase the desalted water produced from sea water by 337 MCM/year by the year 2000.

The total municipal sewage treated in 30 major plants in the Kingdom exceeds 1.23 million m^3/d, of which only 22 per cent is reclaimed (17). Most of these plants are designed for secondary treatment; tertiary treatment plants include Manfouha North, Taif and Al-Khafji. With two plants each having a capacity of 200,000 m^3/d, the Manfouha plant south of Riyadh is the largest in the country. The reclaimed effluent from Manfouha North is used close to Riyadh for agricultural purposes. On the eastern coast, about 22,000 m^3/d are reclaimed, and the remaining effluent (about 390,000 m^3/d) is disposed of in the Gulf. Several projects are underway to expand Dammam's plant from 180,000 to 440,000 m^3/d and Al-Khobar's plant from 133,000 to 256,000 m^3/d. The effluent from these new plants will be transported to the Al-Hasa region to be utilized in agriculture. The treated effluent from Al-Qatif plant (200,000 m^3/d) is used for landscaping and greening of highways in the Eastern Region.

The Medina wastewater plant is being expanded from 120,000 m^3/d, its present capacity, to 200,000 m^3/d, with the ability to treat up to 320,000 m^3/d during peak flow. The new expansion will include tertiary treatment to allow the use of reclaimed water for agriculture.

TABLE 19. MAJOR SEAWATER DESALINATION PLANTS IN SAUDI ARABIA (1997)

Plant	Capacity m^3/day	Process
West Coast		
Jeddah II	37 850	MSF
Jeddah III	65 700	MSF
Jeddah IV	189 250	MSF
Jeddah RO1	56 800	RO
Jeddah RO2	56 800	RO
Shouaibah I	181 860	MSF
Shouaibah II	378 787	MSF
Yanbu I	181 860	MSF
Yanbu II	99 000	MSF
Yanbu RO	128 400	RO
Assir I	75 700	MSF
King Faisal Naval Base I	7 500	MSF
King Faisal Naval Base II	7 500	RO
Haql II	3 785	RO
Duba III	3 785	RO
Umluj II	3 785	RO
Azizia I	3 870	MED
Dahban JTC	3 500	RO
Jeddah ADC	3 400	RO
Al-Birk I	2 271	RO
KAAA I	25 000	MSF
KAAA II	2 000	RO
KFIP	2 000	RO
Saudia City	4 000	MSF
Saudia City	2 000	VC
Farasan	1 600	RO
Abhur Palace	1 000	RO
Tuwal Palace	1 100	RO
Jeddah Refinery	10 000	MSF
Gizan Port	12 000	MSF
Rabigh Refinery	18 850	VC
Kunfuda	5 000	MSF
Jeddah Islamic Port	18 900	MSF
Al-Wajh	1 500	VC
Jeddah Touristic City I	4 000	RO
East Coast		
Jubail I	116 035	MSF
Jubail II	798 864	MSF
Jubail RO	90 909	RO
Al-Khobar II	193 536	MSF
Al-Khobar III	227 272	MSF
Khafji II	18 624	MSF
Tanajib	13 600	RO
Al-Safaniya	3 785	RO
Ras Mesha'ab	1 450	RO
Tanajib	3 750	VC
Safaniya	7 200	MSF
Ras Tanura	12 000	MSF
United Sugar Company	1 800	METC

G. UNITED ARAB EMIRATES

The United Arab Emirates, located on the southwestern shores of the Gulf, has 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 United Arab Emirates does not exceed 75 millimetres, and the country has resorted to non-conventional sources of water in order to augment the inadequate supplies.

Abu Dhabi has a very extensive scheme for using treated sewage effluent in irrigating municipal areas. The Government of Abu Dhabi has been following a policy of improving the amenities of the island city by providing public gardens and trees, and shrubs and grassy areas along the main roads, the latter watered with TSE. Parklands and playgrounds are irrigated with potable water. The project of using TSE for irrigation amenities was initiated in 1976. The system was designed to accommodate treated effluent from a population of 665,000, and eventually to provide 70 million cubic metres a year. For public health reasons, this use has been restricted to areas where the public has limited access, such as in the central divides in highways. A sophisticated treatment plant provides preliminary treatment by sedimentation and secondary treatment by the activated sludge system. Tertiary treatment is by rapid gravity sand filtration and disinfection by chlorination and ozonation to ensure adequate measures against viral diseases. The plant is designed for BOD and TSS levels of 10 mg/l each. The designed salinity level is 4,000 micromhos, since the sewage available for treatment was initially considerably more saline than the potable water obtained from the desalination plant and from the freshwater supply of the city. After some restrictive measures were taken, the average conductivity of the effluent fell to around 1,400 micromhos, with a range of 1,200 to 2,500 micromhos. This increased the types of plants which could be grown by using TSE, but also increased the public health risks, since the effluent was no longer unpleasant to drink or to use for other domestic purposes. In addition to chlorination, ozone has also been used to achieve higher initial standards of disinfection, on the basis of 7.5 milligrams of ozone per litre of effluent. As an additional precaution, municipal areas readily accessible to the public are not watered by TSE, and where applied, the treated sewage irrigation systems operate under low pressure to reduce the likelihood of the wind carrying irrigation water spray into populated areas.

TSE is supplied by pumping from storage and balancing tanks to a distribution system of local ground storage tanks and towers. The use of road tankers in hauling TSE to irrigation sites is being phased out in order to avoid disruption of the traffic flow. The TSE distribution system is clearly marked to differentiate it from the potable water system, in order to avoid any possible confusion.

IX. SUMMARY AND RECOMMENDATIONS

The present report has reviewed water desalination and wastewater reuse technology and economics in order to facilitate and expand their use as non-conventional sources of water.

A. WATER DESALINATION TECHNOLOGY

Sea water and brackish water desalination technologies have been developed to the degree that they can provide a reliable source of water at reasonable cost. Six basic methods are used commercially today to desalt water. The MSF process is used primarily in large scale seawater dual purpose (water and power) production plants. MED is competitive today in medium-sized seawater plants when waste heat is available. VC is used mostly in small- to medium-sized seawater plants using electrical power (MVC) or waste heat (TVC) as sources of energy. The RO process is used for both sea water and brackish water desalting. It is being used increasingly for larger plants because of its economy and energy efficiency. ED is competitive for desalting low-salinity brackish water. MS is used for water softening as it removes only some of the dissolved salts. Hybrid processes will be used increasingly in the future.

The choice of processes is subject to many interactive variables and to the requirements of each site. Each process has advantages and limitations which should be evaluated by experienced professionals in order to produce water with the desired performance at minimum cost.

B. DESALINATION COST

In 1997 the cost of a desalination unit for large-sized plants was about 5 per cent of the unit cost in the 1960s. The experience of Saudi Arabia and Kuwait indicates that for large-sized seawater plants, a unit cost of \$0.70 per cubic metre can be expected when the plant is operating under optimum conditions. The unit cost of desalting brackish water depends on the salinity and quality of feed water and today can be as low as \$0.20 per cubic metre. Unit capital cost varies typically between \$1,000 to \$3,000/m^3 of production capacity for seawater plants. The equivalent capital cost for brackish plants is about 25 to 50 per cent of the cost of seawater plants, depending on water salinity and quality. The cost of desalted water depends on many factors, including the process type, plant size, feed water salinity and quality, the plant's material specifications, energy cost, plant location and the operators' skills.

C. A PROPOSED APPROACH TO SELECTING A PROCESS

ESCWA countries with high capital and energy costs should consider RO as their first choice of technology for desalting sea water or brackish water owing to the technology's lower capital cost and higher energy efficiency per unit of water produced. In addition, it is possible in the RO process to achieve the lowest unit desalted water cost at a fraction of the production capacity and investment needed to achieve the same economy of scale in thermal plants. It is also possible to build a RO plant and to expand its capacity in a fraction of the time needed for thermal plants. In case of a temporary electric power shortage or oversupply, RO can be used as a buffer with sufficient product water storage capacity. RO technology utilizes relatively standard industrial components that are readily available from many suppliers around the world and can be produced locally when needed. However, the above generalizations may not hold under any one of the following conditions:

1. If very large demand as well as funding for both water and electric power exist, then a dual purpose MSF plant or a hybrid MSF-RO plant may be the optimum choice;

2. If waste heat or steam is available at marginal cost close to the sea and to a major water demand centre, then MED or TVC should be evaluated as an option;

3. If sea water at the only available site is too polluted and/or high product water quality is required for industrial purposes, then MVC may be the better option, if electric power is readily available, or TVC if steam is available;

4. For low-salinity brackish water (less than 4,000 ppm), ED could be more competitive than RO.

Desalination technology users with limited experience should be aware of the following common pitfalls which increase the cost of desalted water and reduce the reliability of the plant:

(a) Under the constraints of cost and time, ignoring the importance of thorough investigations of alternative seawater intake systems and/or processes; ignoring the need for pilot plant testing;

(b) Adopting the design or recommendations of a manufacturer or a supplier without proper evaluation by experienced consultants and advisors;

(c) Accepting lower quality material and fewer than required instruments and controls or needed valves or lower than desirable flow rates in order to save capital cost.

D. Wastewater reuse technology

The type of treatment required depends on the source of wastewater and its intended use. Traditionally, wastewater treatment methods are classified under three stages: primary, secondary and tertiary. Any reuse must occur only after the secondary stage, with additional treatment. In primary treatment, 90 per cent of the settleable solids and some of the suspended material will be removed. In secondary treatment, most of the organic contaminants and suspended matter will be removed using mostly biological processes. The most common process is activated sludge. The other traditional processes include trickling filtration and stabilization ponds or lagoons. Many variations or improvements on the above basic methods exist, such as extended aeration and biological discs. In the tertiary treatment stage, all the remaining physical, chemical and biological contaminants are either removed by filtration or neutralized by disinfection. The most common methods are sand filtration and chlorination. The latest advanced treatment methods that hold great potential to expand water reuse are microfiltration and ultrafiltration, which can remove all suspended matter, organic contaminants, pathogens and viruses in one physical separation process following primary treatment.

Land treatment of municipal sewage through a natural purification process following primary treatment can be very cost effective for wastewater treatment and groundwater recharge. However, a pilot test must verify the effects of site conditions, and a wet dry cycle should be used for land treatment in order to achieve nitrification/denitrification. Recent applications of aquaculture confirm the feasibility of reclaiming all kinds of wastewater through the use of known water plants such as reeds. The roots of the water hyacinth can absorb most of the contaminants as nutrients and produce quality reclaimed water. Aquaculture application in arid zones should be carefully evaluated because almost 30 per cent of the wastewater will be lost by evaporation in such plants. Unless the plant has economic value, it may be difficult to justify the loss of water.

E. Water reuse economics

Most of the cost of water reuse in large urban areas is related to wastewater collection and reclaimed water distribution. Less than one third of the cost is attributed to the treatment process. The typical unit cost of treating municipal wastewater on a large scale ranges from $0.10 to $0.50 per cubic metre. This range may increase by a factor of two or three for small-scale plants and for industrial or agricultural drainage water. The range of unit capital costs for treatment also varies by treatment level, type of process and land cost. Advanced treatment may cost as much as seawater desalination. Hence, it is important to account for all factors when evaluating water reuse options.

F. Recommendations

1. The selection of the desalination process and the location of possible sites should be carefully evaluated in the light of total project requirements. The RO process should always be considered as an option to compare costs and performance. Hybrid solutions should be considered for large-sized plants and expansion of existing plants.

2. Selection of the optimum water reuse technology for large urban applications should take into consideration the high cost of central wastewater collection and reclaimed water distribution. Present technology could make localized distributed treatment and reuse more economical without additional health risks or environmental cost. The optimum treatment level and method will depend on the specific reuse of reclaimed water. Recycling the reclaimed water will require advanced treatment to prevent the accumulation of hazardous contaminants which may not be critical for a single reuse.

3. The member States of the ESCWA region should adopt integrated approaches for planning and management of their water resources in order to facilitate the utilization of non-conventional water resources.

4. Government legislation should not only specify the quality of potable water or the quality of reused water for various applications, but should also encourage self-control because of the difficulty most Governments encounter in enforcing any legislation. Self-enforcement can be encouraged by making all those involved in the production and distribution of water responsible for the consequences of its use.

5. All ESCWA member countries need to improve their training programmes in advanced water technologies. Existing programmes are fragmented and inadequate. Training programmes for technicians, professionals and executives should be integrated with each country's present and future water policies, plans and infrastructure. The availability of well-qualified local people is the most important requirement for national water security and economic efficiency. Regional organizations such as ESCWA should facilitate regional cooperation in developing training material and programmes in Arabic.

6. The need for continuous research and development programmes is another requirement for water sufficiency and efficiency in arid countries. All ESCWA members need to make more tangible long-term financial allocations for research and development in water sciences and technologies. Great savings could be realized by regional cooperation in such programmes. ESCWA could also play a more active role in facilitating such joint programmes.

7. The ESCWA member countries have many critical problems to solve besides water shortages. Plans and programmes for integrated, long-term, sustainable solutions should be initiated to solve a variety of problems. One such integrated solution would be the future development of desert communities utilizing solar power and saline water as key sources for energy and water. Solar desalination, water reuse, saline agriculture, and aquaculture are some of the key areas of research that need to be integrated into pilot projects to test and develop future communities that will be able to sustain houses and jobs for future generations with the available resources.

8. There is a need to develop new and innovative financing options for future water works. Privatization of water works should be consistent with the social, institutional and environmental objectives of each country, not just its economic objectives. Privatization should be an opportunity to re-evaluate existing institutions and policies in order to meet the future aspirations of each country. It should not be used as a tool to facilitate the implementation of specific projects without due consideration of its social and political impacts.

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