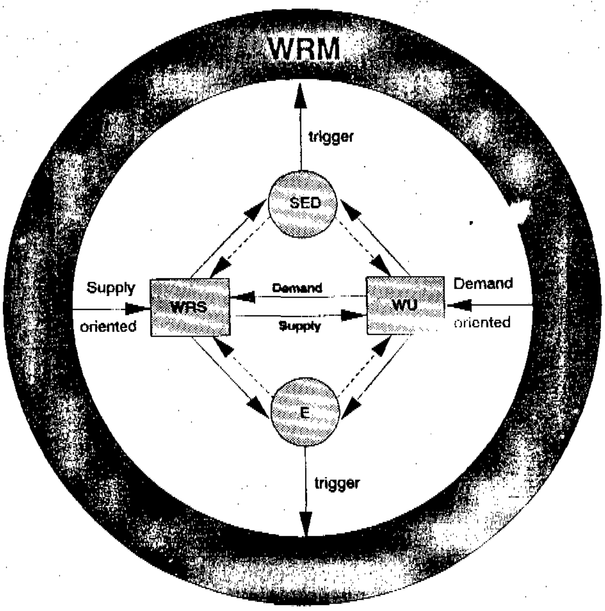
H.H.G. Savenije

WERM011/96

Water Resources Management Concepts and Tools



IHE DELFT

International Institute for
Infrastructural, Hydraulic and
Environmental Engineering

The Netherlands

H.H.G. Savenije　Lecture Notes　WERM011/96

Water Resources Management
Concepts and Tools

Dr. H.H.G. Savenije Delft, November 1996

WATER RESOURCES MANAGEMENT
CONCEPTS AND TOOLS

CONTENTS

Preamble

The lecture on Water Resources Management, Concepts and Tools is a compulsory subject of three courses: the Water and Environmental Resources Management (WERM) Course (both for WQM and WRM branches), the Course for Hydrologists, and the Hydroinformatics Course. It is meant to give an introduction to present-day views and techniques regarding the sustainable management of water resources as an integrated part of the national policy framework. It is the basic lecture for the Water Resources Management (WRM) branch of the WERM Course. It is part of a sequence of key lectures on planning, analysis, management and decision making:

- Framework for Analysis; focusing on an integrated systematic approach to planning and analysis;
- Planning Economics; focusing on analyzing the costs and benefits of actions in both monetary and non-monetary terms;
- Management Arrangements; focusing on the implementation mechanisms for integrated water resources management;
- Decision Making and Communication; focusing on techniques to facilitate the comparison of alternatives and the communication with stakeholders;
- Water Using Activities; focusing of the claims that water users lay on the water resources system and the impacts they may have on it;
- The INCOMANA groupwork which integrates all the theoretical concepts and tools learned in the WERM course into a real-life planning case;
- The various Roleplays that give real-life and hands-on experience of how water resources managers and stakeholders operate.

These lecture notes address the basic components of water resources management: the water resources system, comprising the water resources, the physical infrastructure and the institutional framework, and the water demands as expressed by the different water users. It describes their particulars and the way these components interact. Chapter 3 on Water Resources, to some extent, contains redundant material which has been lectured in the lecture Principles of Hydrology. The redundant material is not presented in this lecture series, but has been retained in the lecture notes for reasons of completeness.

Water in The Netherlands

The Committee for Hydrological Research, TNO-CHO issued an interesting booklet called "Water in The Netherlands (1986, 1989). Besides general information on the history of water resources management, the climate and water works in The Netherlands, the booklet gives extensive information on the present organization of the Dutch water sector, the management of both quantity and quality of water, and most importantly on the water administration and water resources management (Chapter 8). Since the institutional arrangements of The Netherlands are considered interesting for IHE participants, this Chapter is fully reproduced in Section 2.5.

1. CONCEPTS IN WATER RESOURCES MANAGEMENT

1.1. Definitions

This Section deals with the definitions of the terminology used in the water sector with regard to planning and management. Definitions are given of water resources management, integrated water resources management, sustainable use of water resources and water resources capacity building.

WATER RESOURCES MANAGEMENT

Three activities are distinguished: **Water Resources Development** (WRD), **Water Resources Planning** (WRP), and **Water Resources Management** (WRM). Water Resources Development is defined as:

> **Water Resources Development:** actions, both physical and administrative that lead to the beneficial use of water resources for single or multiple purposes.

People from different backgrounds seldom have the same idea about what water resources development means (see Fig. 1.1). To those living in an arid country, it means drought relief, food, jobs, law and politics. To those living in humid areas, it brings to mind waterworks, flood protection, navigation, hydropower and pollution control. To the ecologist, water resources development is often connected with the deterioration of habitats, the destruction of natural rivers and pollution. To the water resources engineer, water resources development is related to dams, reservoirs, flood protection, diversions, river training, water treatment and reclamation. To the lawyer, a water resource system is a device for the implementation of water rights. To the economist, water resources development is connected with economic efficiency, stimulation of growth, poverty alleviation and employment generation. Similar specialized viewpoints are held by politicians and decision makers.

Water resources development includes all these points of view. It is physical, economic, political, sociological, environmental, agricultural and technical. The relative ease with which one of these aspects might be quantifiable, as compared to another, does not in any way reflect a correspondingly great importance. If not enough weight is given to either one of these aspects, a water resources development project is likely to fail.

Hence the planning of WRD is **multi-disciplinary**. It is defined as:

> **Water Resources Planning:** planning of the development and allocation of a scarce resource (sectoral and intersectoral), matching water availability and demand, taking into account the full set of national objectives and constraints and the interests of stakeholders

Hence WRP is multi-sectoral, multi-objective and multi-constrained. Planning is only effective if all interested parties (both formal and informal) during the planning and implementation stage (stakeholders) are - in one way or another - involved in the process of decision making and hence feel committed. If not, the project(s) or programme is likely to fail.

What is Water Resources Development ?

- to people in arid countries:
    - drought relief
    - irrigation
    - jobs, food
    - flash floods
- to people in wet countries:
    - water works
    - navigation
    - flood protection
    - hydro power
- to the water engineer:
    - dams, reservoirs
    - flood protection
    - river training
    - water treatment
- to the environmentalist:
    - habitat deterioration
    - deforestation
    - pollution
    - destruction of wet lands
- to the lawyer:
    - legislation
    - international law
    - water rights
- to the economist:
    - stimulation of economic growth
    - poverty alleviation
    - employment generation

Fig. 1.1 How do people from different backgrounds consider Water Resources Development

The management of water resources is defined as:

> **Water Resources Management: the whole set of technical, institutional, managerial, legal and operational activities required to plan, develop, operate and manage water resources**

Water Resources Management can be considered as a process including all activities of planning, design, construction and operation of water resources systems.

Hence: WRM > WRP

Water Resources Management integrates by definition all aspects and functions related to water. The term **Integrated Water Resources Management**, IWRM, is defined as WRM that takes full account of:

- all natural aspects of the water resources system: surface water, groundwater, water quality (physical, biological and chemical) and its physical behaviour;
- the interests of water users in all sectors of the national economy (agriculture, water supply, hydropower, inland transportation, fisheries, recreation, environment, nature conservation); hence the complete mix of inputs and outputs related to water;
- the relevant national objectives and constraints (social, legal, institutional, financial, environmental);
- the institutional framework and stakeholders (national, provincial, local);
- the spatial variation of resources and demands (upstream-downstream interaction, basin-wide analysis, interbasin transfer).

In fact, good water resources management is integrated water resources management and the addition of the word "**integrated**" is merely used for emphasis.

SUSTAINABLE USE OF WATER RESOURCES

Water resources development that is not sustainable is ill-planned. Fresh water resources are scarce and to a large extent finite. Although **surface water may be considered a renewable resource**, it only constitutes 1.5% of all terrestrial fresh water resources; the vast majority is **groundwater (98.5%) which – at a human scale – is virtually unrenewable**. Consequently, there are numerous ways to jeopardize the future use of water, either by overexploitation (mining) of resources or by destroying resources for future use (e.g. pollution). Besides physical aspects of sustainability there are social, financial and institutional aspects. The following **aspects of sustainability** are distinguished:

- **technical** sustainability (balanced demand and supply, no mining)
- **financial** sustainability (cost recovery)
- **social** sustainability (stability of population, stability of demand, willingness to "pay")
- **economic** sustainability (sustaining economic development or welfare and production)

- institutional sustainability (capacity to plan, manage and operate the system)
- environmental sustainability (no long-term negative or irreversible effects)

Fig. 1.2 (from Koudstaal, Rijsberman and Savenije, 1991) shows a schematic representation of the concept of integrated water resources management for sustainable development. The core of sustainable water resources management is the balance between supply and demand of water related goods and services. The Water Resources System (WRS), which consists of the water resources, the water infrastructure (both natural and manmade) and the administrative infrastructure (institutional framework), supplies goods and services to the Water Users (WU), which are all activities in society that use water, whether consumptive or not. The WRS only supplies water to the WU on the basis of explicit demands, often expressed in a willingness to pay, not on the basis of forecasts or some vague ideas. A direct and explicit interest from the WU is a condition to guarantee the sustainability of the supply, both in terms of quality and quantity.

In the interaction between WRS and WU, Water Resources Development activities take place. These activities have impacts on both the state of the Environment (E) and the state of the Socio-Economic Development (SED) of the planning unit (river basin, region or state). On the other hand, developments are only possible if the state of the environment (E) and the state of the socio-economic development (SED) has sufficient carrying capacity to sustain these developments; these carrying capacities are indicated by the dashed arrows. The double sets of arrows both with regard to impact and capacity and with supply and demand should guarantee the sustainability of the activities. Koudstaal et al. (1992) call this a "bottom-up" approach, as opposed to the traditional "impact oriented" approach. An interesting literature review on carrying capacity based water resources management was made by Kern (1994).

The water resources manager interferes with the system through two types of actions: supply oriented measures, such as building infrastructure, drilling boreholes, or building dams, and through demand oriented measures to influence demand. The water resources manager is prompted to take actions by triggers from society: from the state of the SED or from the state of the E. In this way the cycle is closed.

In the past, most of the attention of water managers has been dedicated to supply, the main task being to match the ever increasing demand projections with options for water supply. As a result, in many parts of the world, the most attractive alternatives for the development of water resources infrastructure have already been implemented and in many places it is hard to think of feasible alternatives for a further increase of the supply. When put against the sharp increase in water demand, which is occurring and expected to increase even more during the coming decades, the problem of water shortage takes dramatic proportions. In short, a further growth of demand is no longer sustainable and increases the problems to be solved by future generations.

As a consequence, leading water resources managers believe that further development should be based on the principle that water is finite, and consequently that the attention should be shifted from managing the supply to influencing the demand (see Section 4.3).

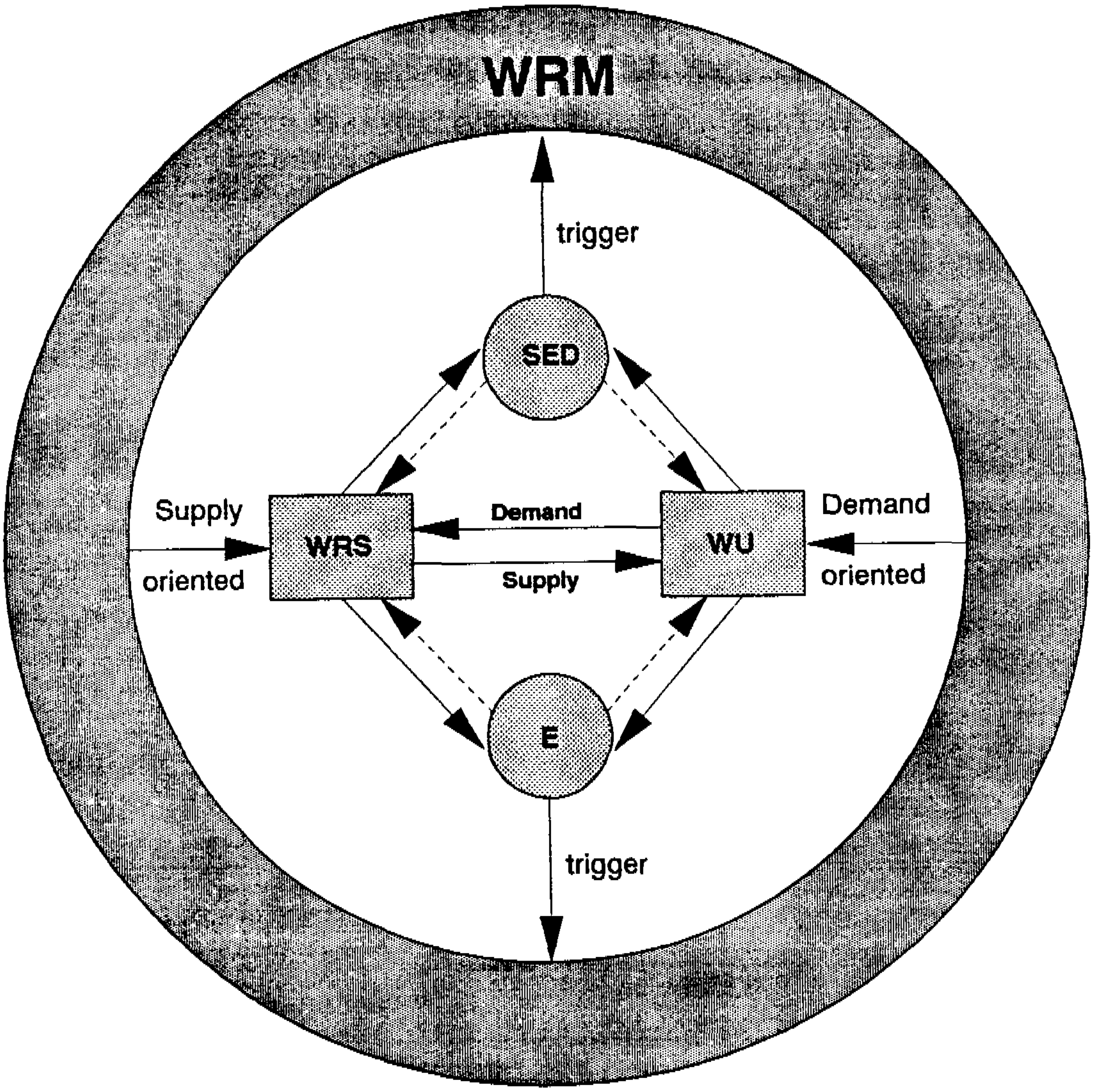


Fig. 1.2 Sustainable Water Resources Management

WATER SECTOR CAPACITY BUILDING

Capacity building in water resources management is required to guarantee **institutional sustainability**; it is defined as:

> **Water Sector Capacity Building:** Activities involving the development of institutions needed for sustainable water resources utilization, (including the establishment of sound management systems and incentive structures, and human resources development), as well as favourable policy environments with respect to all actors involved.

Water Sector Capacity Building has been introduced at the UNDP/IHE Symposium on "A strategy for Water Sector Capacity Building" (Alaerts et al., 1991). At the Technical Consultation on Integrated Rural Water Management (FAO, 1993), **capacity building** was **said to consist** of:

- the creation of an **enabling environment** with appropriate policy and legal frameworks; policy issues to be addressed include a focus on sustainable development, pricing of water as an economic good (see Section 1.2), and the principle of cost recovery;
- **institutional development**, preferably building on existing institutions; institutional development includes national, local, quasi-governmental, public and private institutions, and community participation;
- **human resources development** and strengthening of managerial systems at all levels.

Key actors in capacity building include government at various levels, external support agencies (ESAs), education and training institutes, professional associations, national and international corporations, consulting firms and individuals.

1.2. Strategic Issues in Water Resources Management

In this Section, the present issues in water resources management are briefly introduced. These issues have been discussed in **international meetings** at New Delhi (UNDP, 1990), Delft (Alaerts et al., 1991), Dublin (ICWE, 1992), Rio de Janeiro (UNCED, 1992), Paris (UNESCO/WMO/ICSU, 1993), Rome (FAO, 1993), Delft (IHE, 1993), Cairo (ICPD, 1994) and in the Water Resources Management Policy Paper of the World Bank (World Bank, 1993).

Since the appearance of the Brundtland report "Our Common Future" (WCED, 1987), **sustainable development** has been embraced by planners as the leading philosophy that would on the one hand allow the world to develop its resources and on the other hand preserve unrenewable and finite resources and guarantee adequate living conditions for future generations.

Water resources managers are convinced that if ever the theory of **sustainable development** can be put into practice, that **the role of water in this [illegible] is crucial**. Although this was a clear implicit conclusion of the Dublin (1992) Conference on Water and the Environment, water did not receive the attention it deserved at the UNCED (1993) conference in Rio de Janeiro. It was President Mitterrand of France who made the observation that water is the key to sustainable development and that it did not receive the prominent place it deserved in Agenda 21.

In fact, most of the World's attention at the Rio conference focused on more general issues such as **biodiversity** and the **greenhouse effect** (climate change), both of which are very important but not very tangible. Scientists are not yet completely sure which processes govern and threaten biodiversity and climate change. But we know that the activities of Man are important in the reduction of biodiversity, in climate change, and - more in general - in exceeding the carrying capacity of the environment. Man's activities are to a large extent dependent on the availability of water and hence water management can and should be instrumental in guiding human activities for sustainable development

It is surprising how little attention is paid to water on the international agenda. If one realizes how controversial and still poorly defined the problems of biodiversity and the greenhouse effect are as compared to the water issue, and how important water is in guiding Man's activities, than it is surprising that there still is no Water Convention, whereas conventions for biodiversity and control of the greenhouse effect have been signed.

In general the awareness of people and of politicians for water issues is small. Except in those parts of the world where water shortage is strongly felt in day to day life, people appear to take water for granted and don't seem to be aware that the limits of water resources development are within reach. And if awareness is low with the people, than awareness is low with the politicians. It is important that ways be sought to raise awareness through education, through communication and through enhanced participation of people in water resources development.

Fortunately this situation is changing. The World Bank is advertising the viewpoint that a global water crisis is looming and that many of the future national and international conflicts will concentrate around water as the most emotive issue, even to bypass land issues. In fact, modern historians believe that conflicts such as in Rwanda and Bosnia, are resource conflicts rather than ethnic conflicts which find their origin in sharing scarce land and water resources. Ecologists tend to agree. Brown (1995), in the State of the World 1995, states: "Rwanda is a tragic example of a war as a result of ecological stress"

The sharing of **international water resources** is a possible source of conflict between riparian countries. Worldwide, there are 215 international river basins, constituting 47% of the total area (Gleick, 1993). In Africa, South America and Asia this percentage is higher (more than 60%) probably as a result of colonial divisions. In several regions of the developing world, water is one of the main reasons for, or even the root of, **international conflicts**. Particularly where water resources are a limiting factor for development, conflicts are likely to arise. In future, under the influence of population growth and economic growth, these conflicts are to become more numerous and probably more violent, if no adequate action is taken. International rules on the use of water of international rivers have been developed long ago: the Helsinki Rules (ILA, 1966) and a law is under preparation (UN, 1991), but this issue warrants more attention by international organisations and ESAs alike.

Whether or not we shall succeed in reaching sustainable levels of development shall depend, to a large extent, on two factors that are out of the reach of water resources management: **population growth** and **economic growth**. From the viewpoint of sustainability, the world population should stabilize and overall economic growth can not be more than moderate, based on the availability of renewable resources. Although in developing countries, in general, there still is ample scope for development and for economic growth, in the industrialized world there are strong indications that the sustainable level of development has already been exceeded. The consequence of this is that in the developed countries one should look for ways to **formulate and implement zero-growth scenarios**. In developing countries it is essential that the population be kept in balance with the environmental carrying capacity, which, in most cases, implies strict limitations on population growth.

In Cairo, at the International Conference on Population and Development, important issues were addressed with regard to population control. A very important conclusion of the conference was that the responsibility of how many children a family should have lies with the parents and primarily the women. The conference concluded that, in order to do so, women should have access to reproductive health care and should be empowered to take adequate decisions on the health and prosperity of their own family. An important recommendation of Cairo was that women, particularly girls and young women, should have access to schooling and education. The general feeling was that educated and empowered women will generally take the decisions which are best for their family, for a sustainable future and, hence, for society.

Consequently, the way in which population growth can be influenced by natural resources managers is through facilitating **education** and access to **reproductive health care** for women. Such measures should be part of national strategies for natural resources management. Moreover one can say that where adequate living conditions are present (adequate water supply, sanitation, health care and education, and sound socio-economic perspectives), people are more likely to consider family planning then in situations where these conditions are lacking.

Although Cairo has opened new approaches to limitation of population growth, the question of limiting economic growth in overdeveloped countries remains unaddressed. Unfortunately, both population growth and economic growth are generally considered exogenous scenarios to water resources management.

One of the most important activities that have to be deployed during the coming years is **demand management**. In the past, the attention of water resources management mainly focused on supply management: making sure that enough water is made available for the different users, without taking into consideration whether the (often exponential) growth of the demand could continue indefinitely. Since the Dublin Conference, water managers agree that we should actively search for ways to implement demand management through economic, administrative and legal implementation incentives.

Since Delft (Alaerts et al., 1991) and Dublin (ICWE, 1992), the integrated, also called holistic, approach to water resources management has been accepted as a guiding principle. **Integrated water resources management** implies integration in terms of:

- the **different physical aspects** of the water resources (surface water, groundwater, water quality)
- its **spatial variation** (upstream, downstream) resulting in a river basin approach
- the **different interests** of water users and economic sectors
- the **institutional framework**
- the complete set of **national objectives and constraints**

Particularly the latter three non-technical elements require an institutional set-up that allows adequate **intersectoral linkages**. These linkages should not merely exist at the top level. Since Dublin it has been accepted that decision making should be **decentralized** until the **lowest appropriate level**, meaning that only those decisions are taken at the top level that can not be solved at lower institutional levels. It is presently believed that intersectoral linkages should be mainly built on existing institutions and that the creation of new governmental bodies should be avoided where possible.

In the Delft Symposium on Water Sector Capacity Building in 1991, institutional issues of water resources management were discussed. **Water Sector Capacity Building** is creating the enabling environment for implementing integrated water resources management (including the policy and legal framework, the institutional framework and the human resources). It was agreed that present day knowledge has gone far in understanding most of the water related problems that we are facing, and that we know along which lines solutions can be found. What we lack in the developing countries is the capacity to carry out appropriate research, to gather adequate information, to implement measures, to operate water resources systems and to supply adequate services.

It has been expressed in **Rome**, at the Technical Consultation on Integrated Rural Water Management in 1993, that there appears to be a **large need for the exchange of experiences and knowledge** between countries and particularly among developing countries. Not only is the transfer of knowledge from industrialized countries to the developing world important and are financial means for transfer insufficiently available, there is an even larger demand for setting up facilities for developing countries to exchange problems, experiences, solutions, research results and education in a regional context. In Delft, at the Conference on Water and the Environment, Key to Africa's Development, in 1993, this point was strongly emphasized by African participants. In addition the lack of career opportunities, the occurrence of brain drain and the lack of an African knowledge base are considered major constraints for development. It was observed that it is disturbing to realize that most of the knowledge about Africa is concentrated in Western institutes and universities, and that no regional centre of excellence in Africa exists that could assist in policy development.

As a result of ever more powerful computing facilities, it has been possible to show that the **relation between land use and climate**, at a regional scale, is significant. Studies in the Amazonas (Lettau e.a., 1979) and in the Sahel (Savenije & Hall, 1993; Savenije, 1995, 1996) have shown that the relation between rainfall and vegetation cover is strong and that the further one travels inland, **the more important the recycling of moisture becomes**. This aspect forms a direct and important feedback mechanism between rainfall and human activities, such as deforestation, firewood collection, forest clearing, land use, overgrazing and other agricultural practices such as shifting cultivation and irrigation. It also means that once the relations have been established, the direct benefits, both economic and environmental, of remedial actions to restore the climate through the restoration of vegetation can be determined on the basis of physical relations.

Finally there is an **enormous need for reliable and adequate management information**. The recent WB/UNDP Hydrological Assessment of Sub-Saharan Africa has shown that the observation and monitoring networks in Africa are in a miserable situation. But also in other parts of the developing world, data collection has received low priority in view of the huge economic and social problems that developing countries are facing. However, no sound and integrated water management is possible without adequate information, both on water resources and water use. Fortunately, the technical instruments that have come available in recent years, such as: powerful computers, sophisticated software, remote sensing facilities, telemetry systems, etc., have widened the scope of water managers substantially. The time that data collection was considered as an objective in itself has past. Presently, the requirements of models that describe our natural system determine the need for information. Networks should be designed and operated on the basis of physically based models in a way that minimizes the discrepancy with the real world in the most efficient way.

1.3. Activities involved in WRM

The management of the development of water resources is a complex activity. It comprises the full range of activities in the development of water resources, from demand analysis through planning, design and construction to operation and monitoring. In a sense, these activities are sequential: analysis comes before planning, and planning comes before design; but more importantly, there are numerous places in the process where back-loops and feed-backs occur, where new information urges new views and new decisions have to be taken. Water Resources Management (WRM) is a highly dynamic process, covering a wide spectrum of activities in the fields of assessment, planning and operation. Some of these are listed below:

Assessment:
- water resources assessment
- environmental assessment

Planning:
- problem analysis
- activity analysis
- demand analysis
- formulation of objectives and constraints
- demand forecasting
- design of alternative water resource systems

- system analysis
- system simulation and optimization
- sensitivity analysis
- multicriteria and multiconstraints trade-off analysis
- selection and decision making
- involvement of stakeholders
- communication, negotiation and conflict resolution

Operation:

- allocation of resources
- demand management
- management and administration of water institutions
- operation and maintenance
- monitoring and evaluation
- financial management and performance auditing

The activities are highly multidisciplinary, involving, engineers in the area of hydrology, hydraulics, construction, water supply, sanitation, hydropower, irrigation, and non-engineers such as: environmentalists, ecologists, lawyers, economists, sociologists, agriculturists, politicians and representatives of interested parties, pressure groups, and water users.

In this list, the activities are not yet structured, they are a mere enumeration of activities involved in planning and management. In the lecture Framework for Analysis, a[redacted]al [redacted]work is presented identifying the relations between the planning activities and the steps to be followed in a planning cycle.

In our definition, WRM includes WRP. The expression: water resources planning and management is identical to water resources management. However, there is good reason to consider WRP as a separate activity within WRM. Many of the complexities of WRM are related to the planning of the development of the resources. Techniques to cope with uncertainty, to compare alternatives for development and select the most promising alternative, which may be considered the major challenges of WRM, lie in the field of planning. WRP is a permanent activity, not only on a national or regional scale, but at the scale of any complex water resources system. Such a system is never completed in the sense that no further development is possible or necessary. The planned system is implemented in stages, each stage lasting sometimes several years, and the changing technology, demand, political and socio-economical conditions require a permanent readjustment of the existing system and an adjustment of the planned development. The planning of water resources development, thus, has a sufficiently large domain for engineers to exclusively specialize in. However, as a result of the many moments of decision making which occur during the planning process, there is a close interaction with management. Consequently the activity is and should be fully integrated in WRM.

In the past, there was a strong bias in WRP to optimization. This was so strong, that to some people, WRP was almost identical to optimization (linear programming, dynamic programming, etc). Nowadays, it is widely recognised that optimization techniques serve a limited purpose. The reason for this lies in two key elements of planning, which together are largely responsible for the complexity of WRP:

- uncertainty of scenarios
- conflict of interests
- political reality.

If there were no uncertainty and conflict of interest, the planning of water resources would indeed be a simple optimization problem. In addition, the political reality of the moment does not always permit the implementation of "optimal" solutions. The final decision is generally a result of the balance of power. Optimization is only useful as a component of WRP where boundary conditions can be considered as fixed.

1.4. Coping with uncertainty

Uncertainty exists in almost all scenarios that form the boundary conditions for planning:

- hydrologic scenarios: occurrence of droughts, floods disasters; within the full spectrum of uncertainty probably the most simple scenario to forecast with a reasonable accuracy;
- financial and economic scenarios: the development of commodity prices, energy prices, exchange rates, or inflation;
- socio-economic scenarios: population growth, level of consumption, unemployment rates, willingness to pay, mentality, acceptability of measures, attention of the public for water issues;
- political scenarios: changes in government, changes in political system, outbreak of wars, policy changes, e.g. towards small scale versus large scale, the question of whether the emphasis will lie on guaranteeing some of the water for all, or most of the water for some, privatized or subsidized water, development of bilateral relations between riparian countries which share a river basin;
- technological scenarios: the capacity to develop resources for a certain price will change as a function of the technology available.

Some of these scenarios are highly unpredictable and depend on global developments such as energy prices, international conflicts, economic recession, etc. A plan which has been shown to be "optimal" in relation to a certain combination of the above scenarios may prove the "worst" scenario under another combination of scenarios.

This could easily lead to the cynical conclusion that the only thing sure about a plan is that it will not come true. However, there are ways to cope with uncertainty; and some of the techniques involved are briefly discussed below.

The objective of planning should not be to find the "optimal" alternative; it should search for an alternative which behaves well under a wide range of different scenarios. Such a plan is called a "robust" plan. If alternative plans are evaluated for their robustness instead of their optimal performance, a much better basis is created for future development. A robust plan keeps as many options as possible open for future development (see Fig. 1.3). This approach of taking a short term decision that leaves maximum scope for future policy changes is also called strategic planning (see Section 1.5).

An important technique to check alternatives for robustness is sensitivity analysis. If the performance of a certain alternative is very sensitive to a boundary condition incorporating

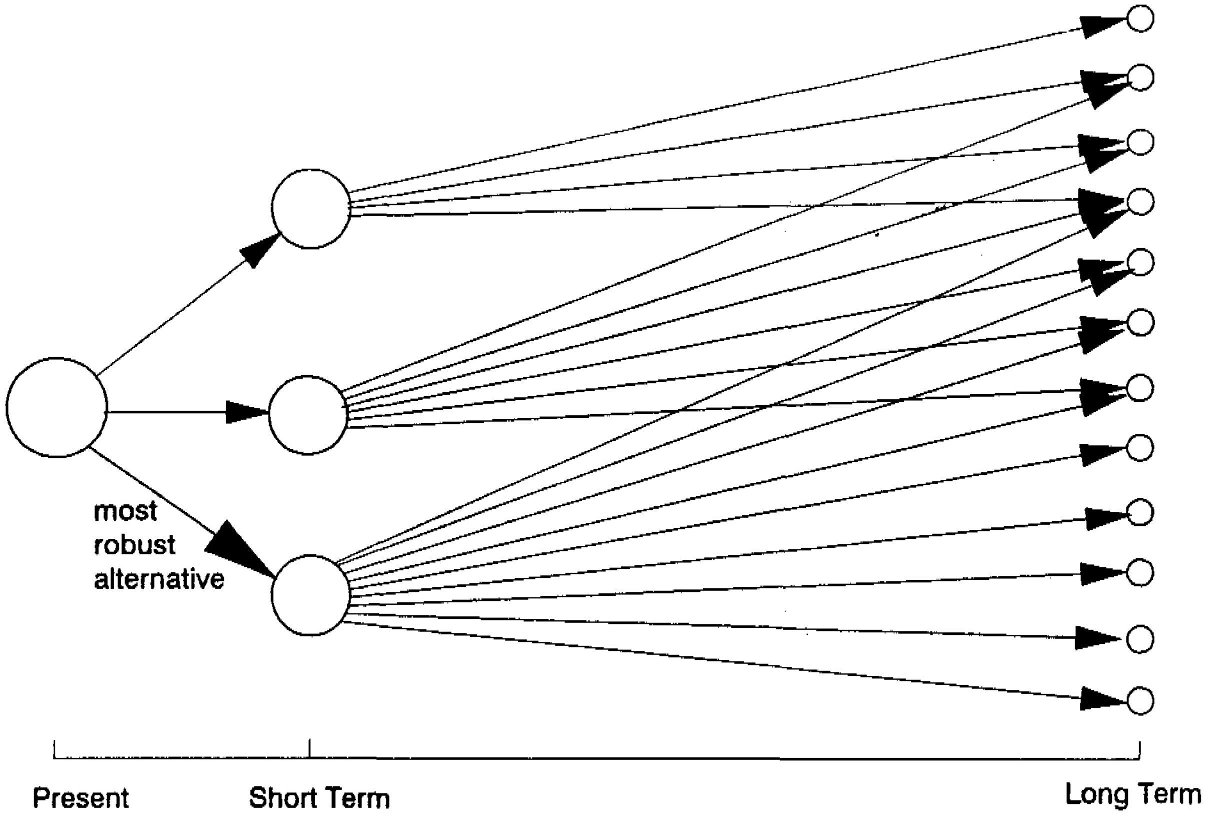


Fig. 1.3 Keeping your options open

a high level of uncertainty, then the alternative ranks low.

Because water resources planning is a permanent activity, the objectives, constraints and boundary conditions of a planning process may, and probably will, change during the planning period. As a result of this uncertainty the planning has to be flexible. It has to allow back-loops, feedbacks, and adjustments to be made to incorporate new information, new interests or new policies. Also the appearance of new techniques, software and hardware, or new insights may lead planners to reconsider certain options.

The tools used to show the effect of different policies, scenarios, and alternative measures on the output of a complicated water resource system should also be flexible. They should not be so complicated that they take a long time to get started or to make adjustments. If calibration or adjustments take too long, then the opportunity for strategic decision making may be lost. They should be highly interactive and flexible simulation tools that can readily be adjusted to new views or new information to give relevant outputs to the water manager.

1.5. Types of planning

Both the planning itself and the tools used should be flexible. This has lead to a change from the traditional "linear planning process" to the nowadays widely advocated "cyclic planning approach" (see Fig. 1.4). Delli Priscoli (1983) states: "You cannot solve the problem until you have solved it." Actually, it is a recognition that planning is not linear.

Planning is iterative. Certain planning tasks are repeated, to varying degrees, throughout the planning process.

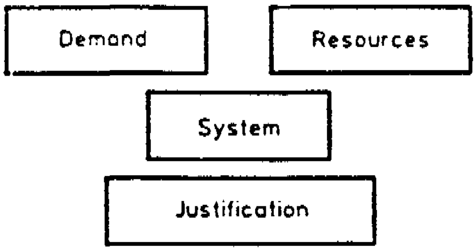
In the linear approach the four major components of water master planning: water resources analysis, water demand analysis, system design and economic and socio-economic justification follow each other sequentially. In a cyclic process, however, this sequence of activities is repeated several times and with increasing detail and accuracy. Thus a full picture of potentials and impacts can already be obtained at an early stage in the process, albeit at a sketchy level. Impossible sequences and undesirable consequences are detected early in the process. This ensures that expectations are adjusted accordingly, and enables further studies and investigations to be specified in accordance with realistic scenarios. Gradually the picture can be painted in finer detail. Another advantage of the cyclic process is that it allows better involvement of stakeholders and creates more possibilities to analyze the carrying capacity of the system (bottom-up approach in Fig. 1.2).

The distinction between linear and cyclic has to do with the way in which the planning process is approached. Besides a distinction in process (linear or cyclic), a distinction can be made in the scope of the plan (after Goodman, 1984):

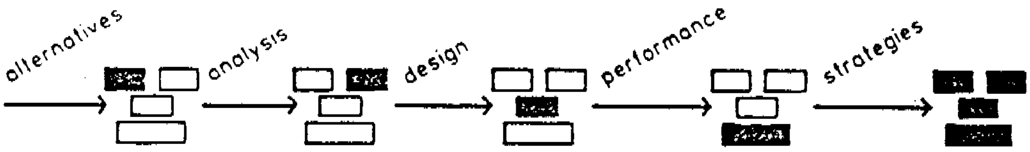
- single purpose plan; a single purpose plan has to do with a single activity, such as water supply, or irrigation, or flood control, or whatever;
- multi purpose plan; a multi purpose plan aims at satisfying a number of purposes at the same time, such as irrigation, hydropower, water supply, environmental management, flood control, etc.; often a multi purpose plan contains several single purpose plans;
- masterplan; a masterplan is a somewhat old-fashioned type of plan; it is the formulation of a phased development plan to exploit the opportunities for single and multipurpose water resources projects in a defined geographic area over a specific period of time; the plan can include a multi-unit system of projects and can encompass both structural and nonstructural elements; however, nowadays we rather use the term integrated plan for something which is slightly more than a masterplan;
- comprehensive or integrated plan; an integrated plan is a multi-unit, multipurpose and multiobjective plan (including economical, financial, political, social and environmental objectives), which considers both structural and nonstructural (institutional) alternatives; a master plan or an integrated plan does not included detailed feasibility studies of individual projects.

Along the same lines, Grigg (1985) makes a similar distinction based on the scope of the planning:

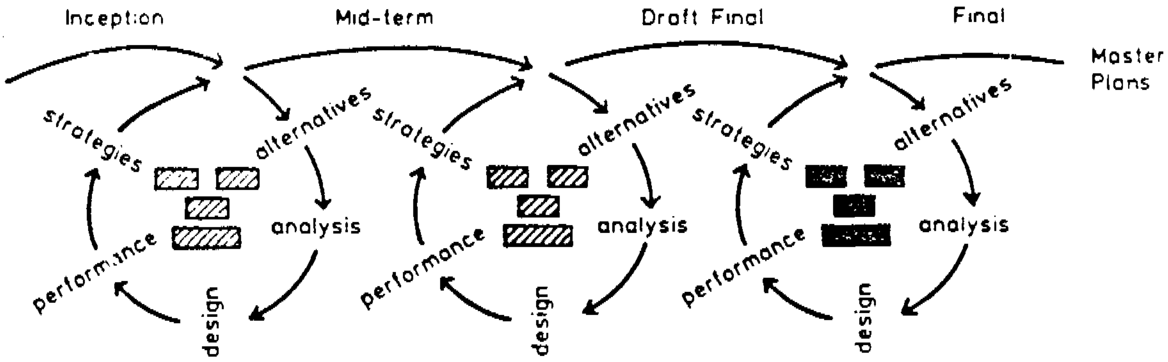
- functional planning; planning to meet a specific need within a sector, such as flood control, irrigation or nature preservation;
- sectoral planning; integrated planning for all functions within one sector, such as water resources, or agriculture;
- multisectoral planning; coordinated planning for all sectors of public endeavour, such as land use, housing, transportation, water resources, waste disposal, and energy supply.



WATER MASTER PLAN COMPONENTS



LINEAR PLANNING PROCESS



CYCLIC PLANNING PROCESS

Fig. 1.4. Cyclic versus linear planning approach

Another distinction often encountered has to do with the areal extent such as:

- national plan; a national water resources plan is made to determine the national priorities for the allocation of scarce water resources in view of the national objectives and constraints; in this respect a national water plan should be an integrated plan;
- regional plan; at regional level a similar exercise can be done, depending on the size of the country; a regional plan, in principle, does not differ from a national plan;
- river basin plan; a river basin plan is particular because it uses the hydrological boundaries as the planning limits; in principle it is should be a multi-unit, multipurpose and multiobjective plan, and hence an integrated plan.

In addition there is a distinction that can be made as regards the time frame of the plan:

- short term planning; short term planning has the advantage that the uncertainty in the scenarios that form the boundary conditions to planning is small; the disadvantage is that a short term plan may lack a vision on future developments;
- long term planning; a long term plan tries to set out a long term perspective and guidelines for the future development of a nation, region or river basin; it has the large disadvantage of uncertainty; as a consequence, short term planning is becoming gradually more important than long term planning; the long term planning is thereby reduced to a long term policy (also called tactical planning), in which the short term plan should leave open a wide range of options that may lead to the ultimate goal;
- such an "open ended approach" is also called "strategic planning"; strategic planning tries to be a combination of the two; it concentrates on the short term in a way that an as wide as possible range of future options remains open (see Fig. 1.3); a plan that foregoes future options and that excludes future development options is not strategic, not flexible and not robust;
- rolling (revolving or continuous) planning; the consequence of the strategic planning approach is that a plan needs continuous updating and continuous adjustment to ever changing circumstances; such a type of planning is called continuous or rolling planning.

It may be clear that strategic and rolling planning lays a heavy claim on the flexibility of the planning tools used in the process. The database and the software used (the Water Resources Information System WRIS) needs continuous updating to adjust to ever changing conditions. It is the challenge of the modern water resources planner to develop and use these flexible tools.

1.6. Involvement of stakeholders

Where resources are scarce, conflicts of interest arise, which are generally politically charged. Changes in the political boundary conditions may change the planning of water projects substantially, especially if the interests of the new group in power had been disregarded before the political transformation.

For a water resource system to function, whether at a local, a river basin, or a national scale, it is necessary that all parties involved are committed to make the system work. This is only possible if they are involved in the planning, design, construction and operation of the system, and if they are convinced that it is in their own interest. The "optimal" plan is the plan which stakeholders accepted as the optimal plan. The only plan that will actually work is a plan based on heavy involvement of the relevant stakeholders, leading to a compromise, or possibly consensus, on design and implementation.

It is certainly difficult to create the institutional setting in such a way that water resources development is sustained by the majority of the people. But it is not impossible. The history of The Netherlands, for instance, has shown that it is indeed possible. The Netherlands is a country that managed its water resources long before the word "water management" was invented. Water management in The Netherlands is much older than the nation itself. In the early Middle Ages many attempts must have been made by small communities to manage the water, because already in the 12th century land had been reclaimed from the sea and inland lakes and swamps had been drained. In the 13th century, people at county level started to protect the land against flooding, to reclaim land from the sea and to control the drainage of low lying areas. The map of the northern part of the County of Holland in 1300 (see Fig. 1.5), shows impressive sea dikes, navigation canals (Rekere), and closure works (Amsterdam, Spaarnedam).

This accomplishment was not brought about without conflicts and without set-backs. There is a clear correlation between political instability, degradation of the water system and the occurrence of disasters. But during the approximate millennium of experience in water management, the institutional solutions have been found to cope with the conflicting demands of different interest groups, in favour of the common good.

The answer to this problem lies in the involvement and the commitment of the parties involved in water resources development; briefly called "involvement of stakeholders". In The Netherlands all stakeholders participate in the maintenance of the water system, either through compulsory participation, (cleaning of canals bordering one's land, dike watch, etc) or through charges (water charges, effluent charges, purification charges, sanitation charges); in addition, interest groups (farmers, water companies, barge owners, environmentalists) participate in the decision process. The traditional maxim of water boards is: "Interest, Payment, Vote". This democratic principle of the water boards is not a consequence of the democratic history of The Netherlands it is the other way round. The Dutch have since early times known some form of democracy (although originally only for the elite) in their water management, as a consequence of their fight against the common enemy: water. Cooperation, consultation and commitment were a condition for survival.

Every country has to organize the development of its water resources in the way that best fits its culture and political tradition. However, the common denominator should be the commitment of all stakeholders.

The cyclic planning approach of Fig. 1.4 offers ample opportunity for involvement. After the completion of a cycle, the results are presented to the stakeholders; a decision is taken on which items need more elaboration in the next planning cycle and on which items the analysis will focus. This ensures that stakeholders participate in the decision process at an early stage, and that they can have an influence on the course of action. Consequently, it

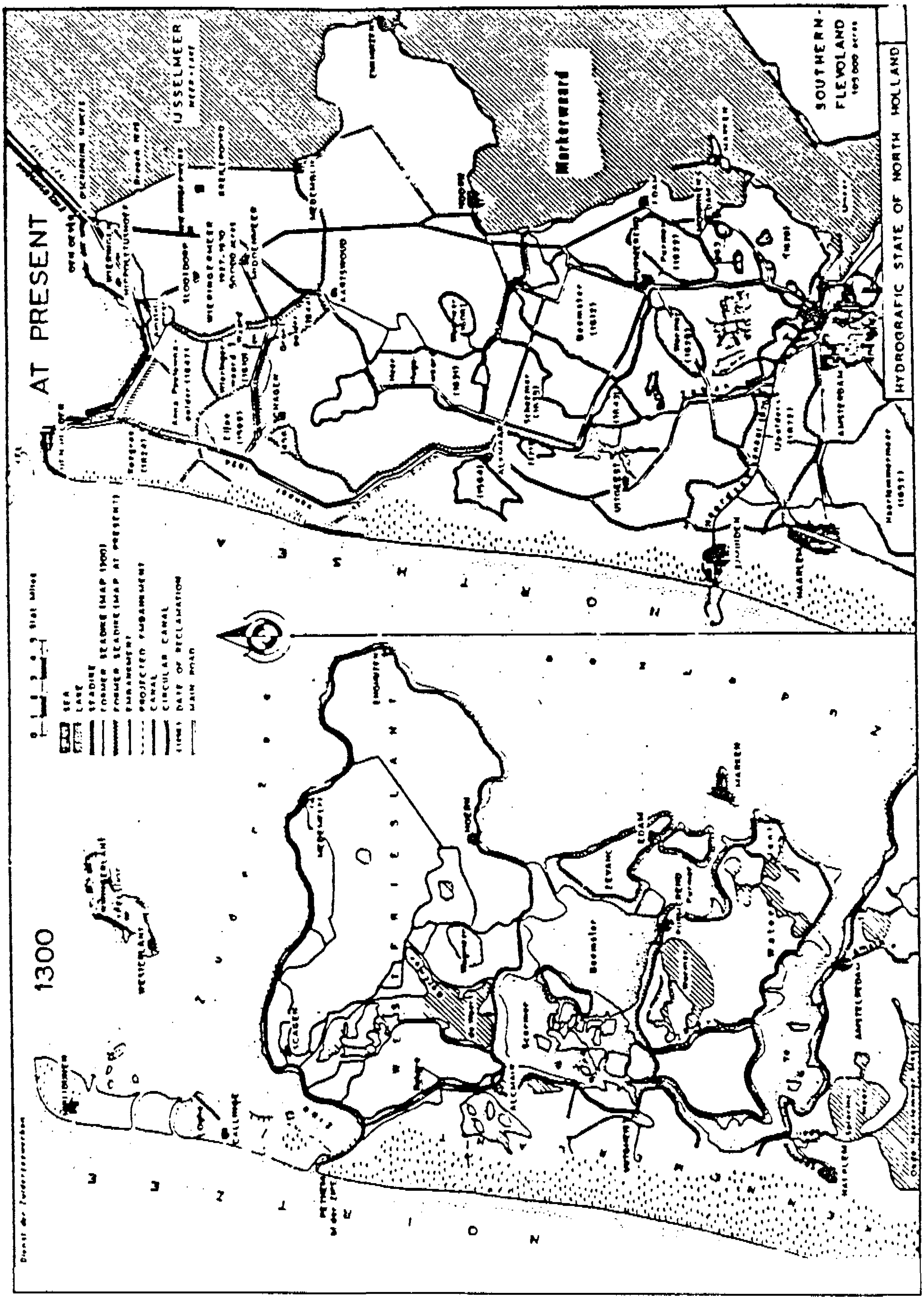


Fig. 1.5 State of hydraulic works in North Holland in 1300 and in 1990

creates the basis for commitment.

In short, it can be stated that in order to be really effective, water resources management should have two characteristics:

- **flexibility** in approach and in planning tools
- **involvement of stakeholders** to achieve commitment

1.7. People's Participation

Many water resources management projects, although technically and economically successful have enlarged inequality and failed to reach and benefit the poor, and most importantly failed to be sustainable in the long term due to lack of maintenance and proper operation.

Some of the main suspected reasons for this are (Mirghani and Savenije, 1995):

- **People don't see the benefits**. Social impacts and the distribution of benefits were not taken into account sufficiently when projects were first proposed. Efforts mainly concentrated on finding a solution to an existing natural problem, such as, for instance, flooding. Possible negative impacts of a flood protection project are: loss of access of the poor to resources (landownership changes), effects of land acquisition (e.g., loss of homestead or fertile land), or decreased fishing potential. Such social and socio-economic changes and loss of access to productive resources could reverse the intended project output leaving the poor majority in a worse situation. Such a situation is a real failure for any development intervention. When people do not really feel the benefits of development, and moreover if the project affects their lives negatively, technical and economical success are of no value.
- **People have no incentive for operation**. Intended beneficiaries of the project often have no incentive to maintain the project, since they were not committed to the project ideas from the beginning; nor were they committed to bearing the responsibility of the development. Moreover, the organisation responsible for operation and maintenance often does not have the financial and physical resources to run the project efficiently.

But are these reasons for project failure or symptoms of an unsustainable planning methodology? **People's Participation (PP)** in project planning and implementation is generally believed to be an important prerequisite to overcome these problems and to make people responsible for the operation and maintenance of the project (ICWE, 1992). Through PP in project identification and preparation (data collection, selection and feasibility assessment), those issues which control the success of the project can be identified and dealt with in the project plan.

When PP is applied to rural water resources projects, the initial emphasis should be on stakeholders' participation. This participation should not be limited to the implementation activities and the sharing of benefits, but should be considered at the very start of the project during problem identification and analysis. People's participation is an important element in socio-economic development and integrated water resources management. A project is only sustainable if it has the support of a broad base of stakeholders, thereby opening up the possibilities both to strengthen local institutions and people's organisations and to develop self-reliance and confidence. For further reading Mirghani and Savenije (1995) is recommended.

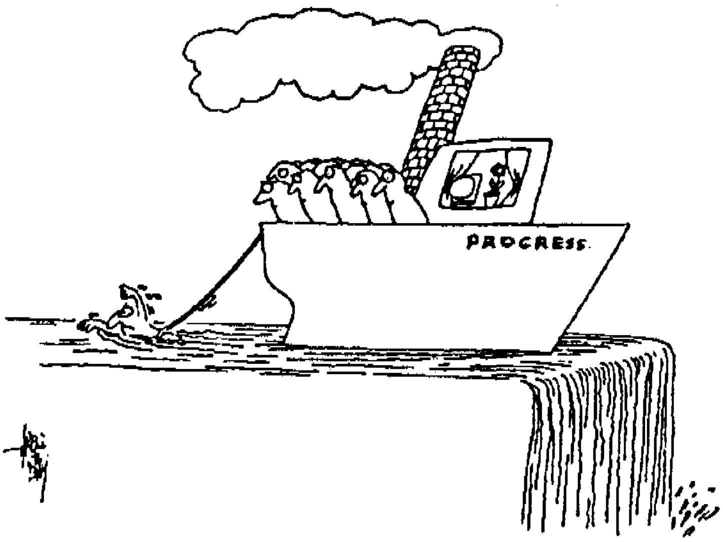
2. HUMAN INTERFERENCES IN THE WATER RESOURCE SYSTEM

2.1. Man's attitude towards nature and development

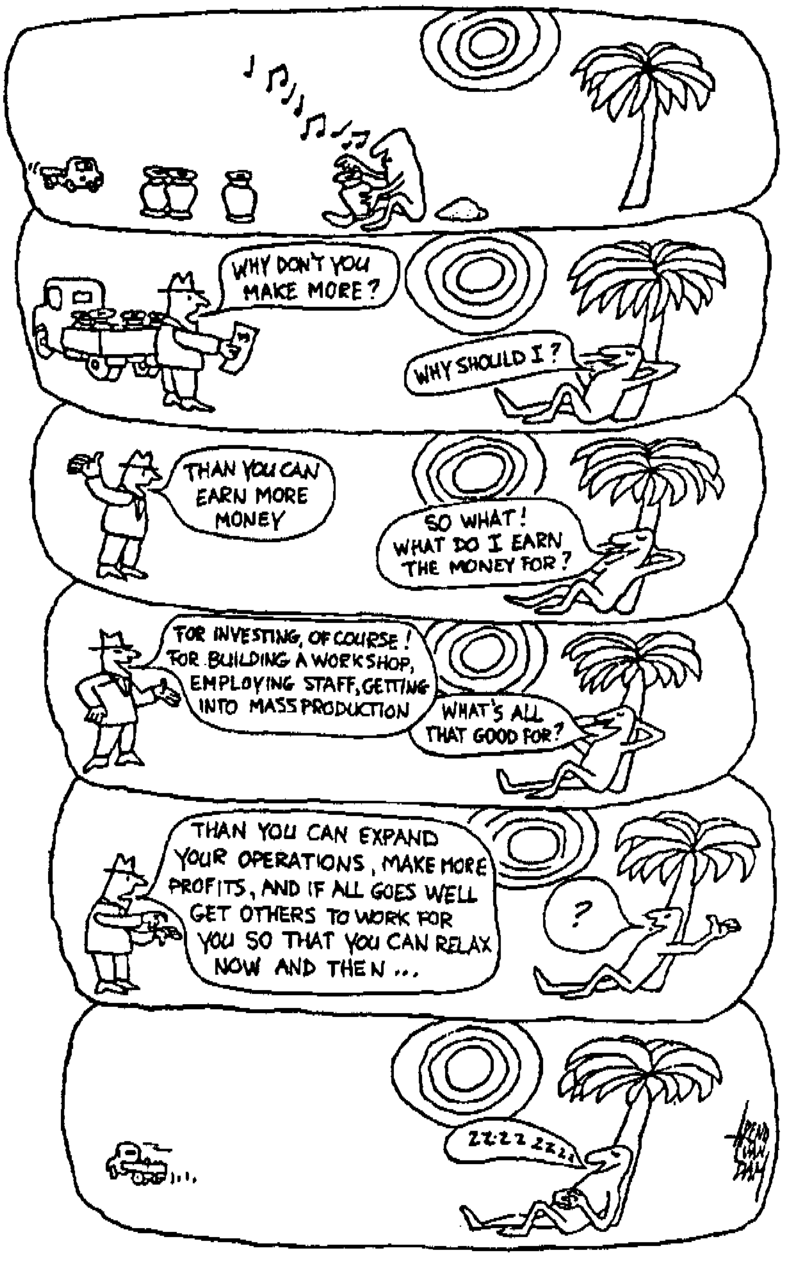
Human action has influenced to a very large extent the present state of the environment. The driving force which led to these actions is simply that humans needed to survive and feed, clothe and house themselves. About the way in which they interfered in their environment, however, it is important to realize what their attitude towards the environment was. Did they look upon the environment as something separate from them or did they consider themselves as being an integral part of the environment? This attitude very much depends on culture and religion.

In the western world, where the exploitation of resources has been most pronounced, both in Europe and in the parts of the world which were colonized by Europeans, the attitude of man towards nature has been very much determined by the teachings of the bible. In this respect the attitude is not essentially different from the attitude in Muslim religion. In Genesis it is clearly stated that the world, the plants and the animals were created for man to benefit from it. The conviction in European tradition is very strong, both in classical (celtic, roman, greek) and christian traditions, that human beings have been put in a position of dominance over nature. Over time, although the culture has changed, this conviction has remained, until recently (the last few years), when the "green movement" started to convince us that man is as much part of nature as animals, plants and natural resources. However, the state of deterioration of the environment that we witness in many parts of the world is the consequence of the philosophy that man dominates over nature and has to fight nature to survive (Ponting, 1991).

Not in all cultures is this conviction as clearly present. Buddhism, for example, considers man as part of nature, and so do several other eastern religions. Also several natural religions look upon man as part of nature.



Another important aspect of western philosophy is the concept of progress (Ponting, 1991). This idea is such a fundamental aspect of modern thought, that it is difficult to imagine that the idea of progress is relatively new. In classical times (roman, greek and celtic) one was convinced of the fact that in earlier times things had been better: the gods were living on earth (the gold age) and that the society had been decaying through silver to the age of iron in which they lived. The idea of paradise at the origin of life in christian and muslim religion is not much different from that. Also Taoist in China, the Cherokee in America and the christians in medieval (Middle Ages) Europe considered the world as a world of decline. It is only after the Enlightenment and the Age of Reason in the 18th century and after the success of physical science and technology (which triggered the industrial revolution), that people started thinking of progress and economic growth as a necessity for survival and even as an economic law.



The concept of market economy is very much related to economic growth. And although there are many countries in the world that have recently accepted the market economy as the principle for their future development (Eastern European countries, China, Vietnam, Mozambique, and many others) there is a fundamental flaw in it. The major problem is that it ignores the fact that resources are finite and that the consumption of finite resources is not sustainable.

Hoogendijk (1993) questions the need for economic growth and advocates zero-growth economies based on the uses of renewable resources. In economic growth scenarios, investments result in more production, production results in more money, more money results in more investments, more money, more production etc. Besides depreciation of money, this "Spiral of Money and Production" leads to exploitation of resources and unsustainable growth.

In classical economic thought, resources do not have a price. The only price they have is the price of extracting them and bringing them to the market. The crucial defect is that the earth's resources are treated as capital. But since resources are finite, they have a price: the price of withholding them from future generations. In the lectures on Planning Economics attention will be paid to this aspect.

This classical economic thinking has lead to a situation where the best way to get rich is by undertaking an environment-unfriendly business and exploitation of resources: trade in industrial and nuclear waste, drugs-trade, arms-trade, trade in rare species, large scale fisheries, etc. Whenever governments try to limit these actions, they tend to be overtaken by criminal organizations.

Human interferences

Man influences the hydrological cycle in several ways, either to protect himself against the water, or to try to make use of the water. The next main activities can be distinguished:

- flood protection,
- irrigation,
- drainage,
- groundwater withdrawal,
- water supply,
- sanitation,
- flow regulation,
- power generation,
- navigation.

Unfortunately there are also a number of unproductive interferences of man, such as:

- discharge of wastes,
- discharge of polluted water,
- pollution of aquifers,
- discharge of cooling water from industrial and thermal plants.

Man tries to control the water resource system through hydraulic structures. These structures are designed taking into consideration the risk of failure acceptable for the specific case. In the following paragraphs, some of the human interferences will be discussed briefly.

2.2. Flood protection

In low-lying and deltaic areas, floods occur regularly both from the sea and the river. The following types of dikes can be distinguished:

- sea dikes
- inland dikes
- river dikes
- submersible dikes
- compartmental dikes
- no dikes

Sea dikes are designed to protect the coastal area against tidal and storm surges. The design situation is generally of a short duration (days), related to the duration of a storm and a spring tide. Sea dikes have to be sturdy to withstand violent wave action. As a result they are generally steep on the landward side and gently sloping on the seaward side.

Inland dikes are designed to protect lowlying areas from flooding. They include polder dikes, dikes surrounding lakes, and canals dikes. These type of dikes are common in the Netherlands. Other inland dikes are sleeper dikes, as a second defence line, and compartment dikes (also for military defence).

River dikes in a temperate climate are different from sea dikes in the sense that they have to withstand high water levels over a longer period of time (weeks, months), whereas wave action is not so strong. This results in a relatively steep slope on the river side and a moderate slope on the landward side. In less temperate climates where flash floods occur, dike slopes on the landward side may be steeper, as they run less risk of failure through seepage.

In a number of cases the no-dikes alternative is desirable. Flooding has a number of beneficial effects. Floods bring nutrients, fish, sediments, allow easy transport, replenish soil moisture, and rinse the land of pests and pollution. Moreover, if floods are gentle (e.g. Chao Phya in Thailand, Chalan Beel and Sylhet in Bangladesh) it is quite possible to grow floating rice. In societies where people live with the floods, the no-dike alternative, accompanied by a number of alleviating measures may be a good alternative. Also in the coastal region, the no-dike alternative may be the best alternative. The maintenance of a sound mangrove belt along the coast is often more effective than dike construction.

Submersible dikes are a compromise between dikes and no-dikes. Submersible embankments are very popular in Bangladesh. In situations where full flood protection is not possible nor desirable, (e.g. for reasons of finance, fisheries, ecology, or environment) submersible embankments offer a good alternative. The objective of submersible embankments is to protect the land against early, unexpected floods, which may destroy a crop just before, or during, the harvest. After the harvest, the dikes are overtopped and the water propagates freely over the flood plain. The advantage of this system is that the embankments are cheap, the flood levels remain low (because no storage is lost), the environment is not much affected, the floods brings nutrients and fertility, fisheries are not jeopardized, spawning grounds are not destroyed, transport by boat is possible during most of the year, the flooding often allows people to cultivate floating rice varieties, and people can be sure of a high yielding variety pre-flood (pre-monsoon) crop which may give a substantial boost to their income.

In Bangladesh (see Fig. 2.1) this has lead to an experiment where controlled flooding is implemented in polders on the left bank of the Jamuna river; the river that discharges almost the entire flood flow of the Brahmaputra, with peak discharges of 100 000 m^3/s. In the FAP 20 project, in Tangail, polders have open connections to the river through inlet structures, which are open during normal floods and are closed when flood levels are too high or too rapidly rising. The polders are divided into compartments that are separated by compartmental dikes containing regulating structures. In each compartment water levels are maintained that are most suitable for the predominant water using activity in the compartment. The operation of the structures is a compromise between fishery interests,

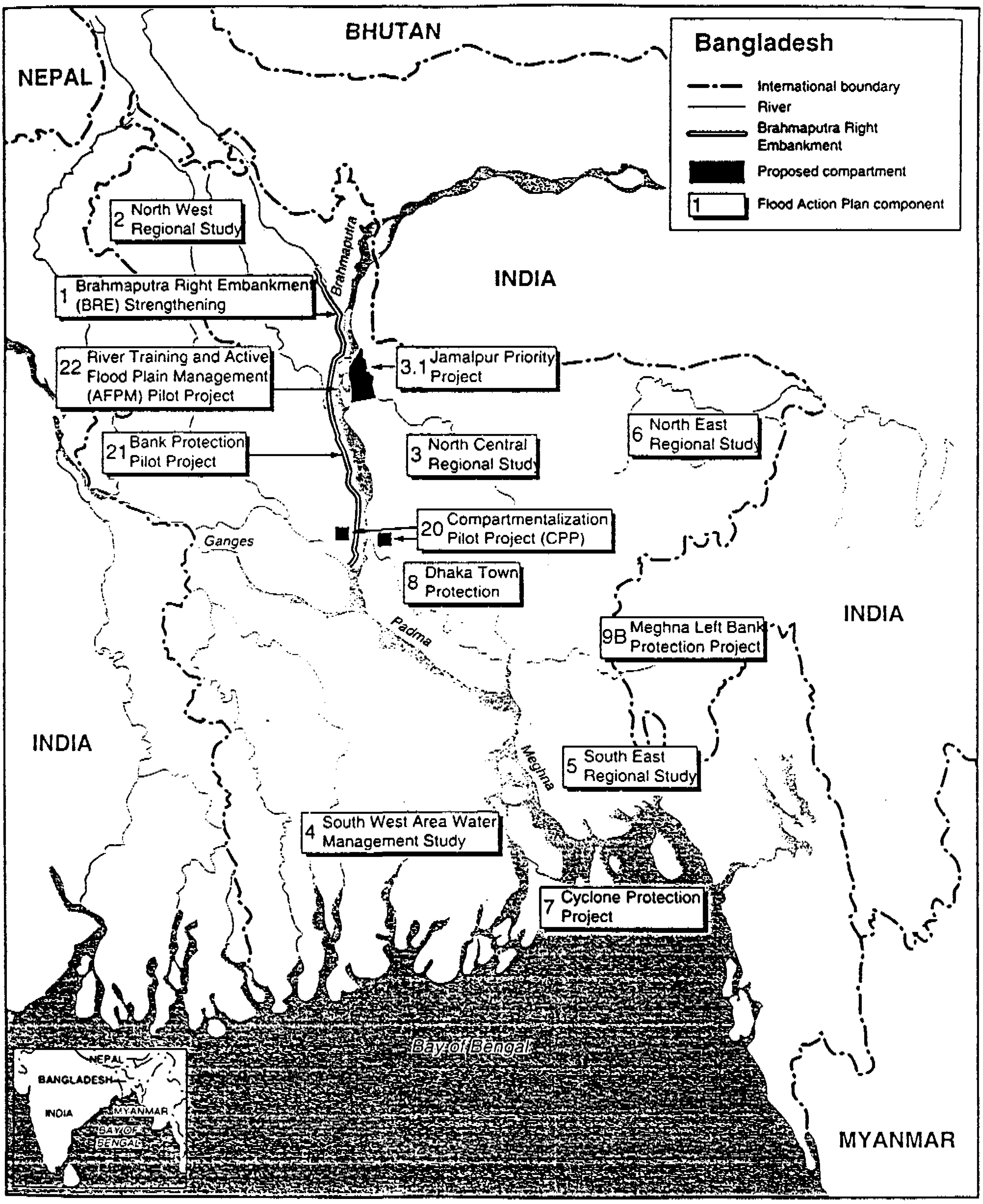


Fig. 2.1 Components of the Bangladesh Flood Action Plan (FAP)

transport interests, and different farming interests.

The Netherlands, see Fig. 2.2, has examples of almost all the mentioned flood protection alternatives. The high economic value of the land permits the enormous annual amounts of money spent on the maintenance and construction of flood protection infrastructure. At present the sea dikes have been designed for a flood with a probability of exceedence of once in 10000 years. The river dikes along the Rhine delta, which protect low lying areas that run the risk of 4-6 m depth of long-duration flooding, have been designed for a design flood of once in 1250 years. For the Maas river, where the damage in case of an inundation is less, the flooding depth is in the order of 1 m and the flooding duration is short, a design flood of once in 500 years is used.

In general the level of protection against flooding is high in The Netherlands. However, if we could have started anew, with the knowledge we have now, we would probably have done a few things differently. The complete protection against river flooding has led to a gradual increase in the bed level of the rivers. The rivers which used to spill their sediment on the land deposited their load in the river bed. The subsiding land, on the other hand, was not replenished with sediment. This meant that the dikes became gradually higher. In addition, the drainage of large areas of land aggravated the land subsidence so that it is now far below sea level. Controlled flooding would probably have been a better alternative.

In fact this development has only been possible, because the rivers Rhine and Maas are relatively gentle rivers, with a slow morphological time scale. If the Dutch rivers had been more vehement, the present flood protection system would probably not have existed.

On the coast, The Netherlands is in the situation that the no-dike alternative is completely unrealistic. The natural situation where land is deposited at approximately mean high water has for many years been disturbed by the interference of man. But in more or less undisturbed deltas, it would be wise to consider maintaining the mangrove protected coast line.

Until recently, in The Netherlands, a situation existed where people did not believe that flooding would ever occur. This was a dangerous situation, because the risk of floods is ever present. Since the floods in the Rhine and Maas of 1995, however, there is again a general concern for the flooding risk. Moreover, the political will to prevent flooding disaster in the future is high. The latest development is that international cooperation on the integrated management of international rivers is receiving renewed attention. Hopefully, the riparian countries will come to better cooperation in the control and prevention of floods, through improved physical planning, coordinated land use and the implementation of flood alleviating and compensating measures.

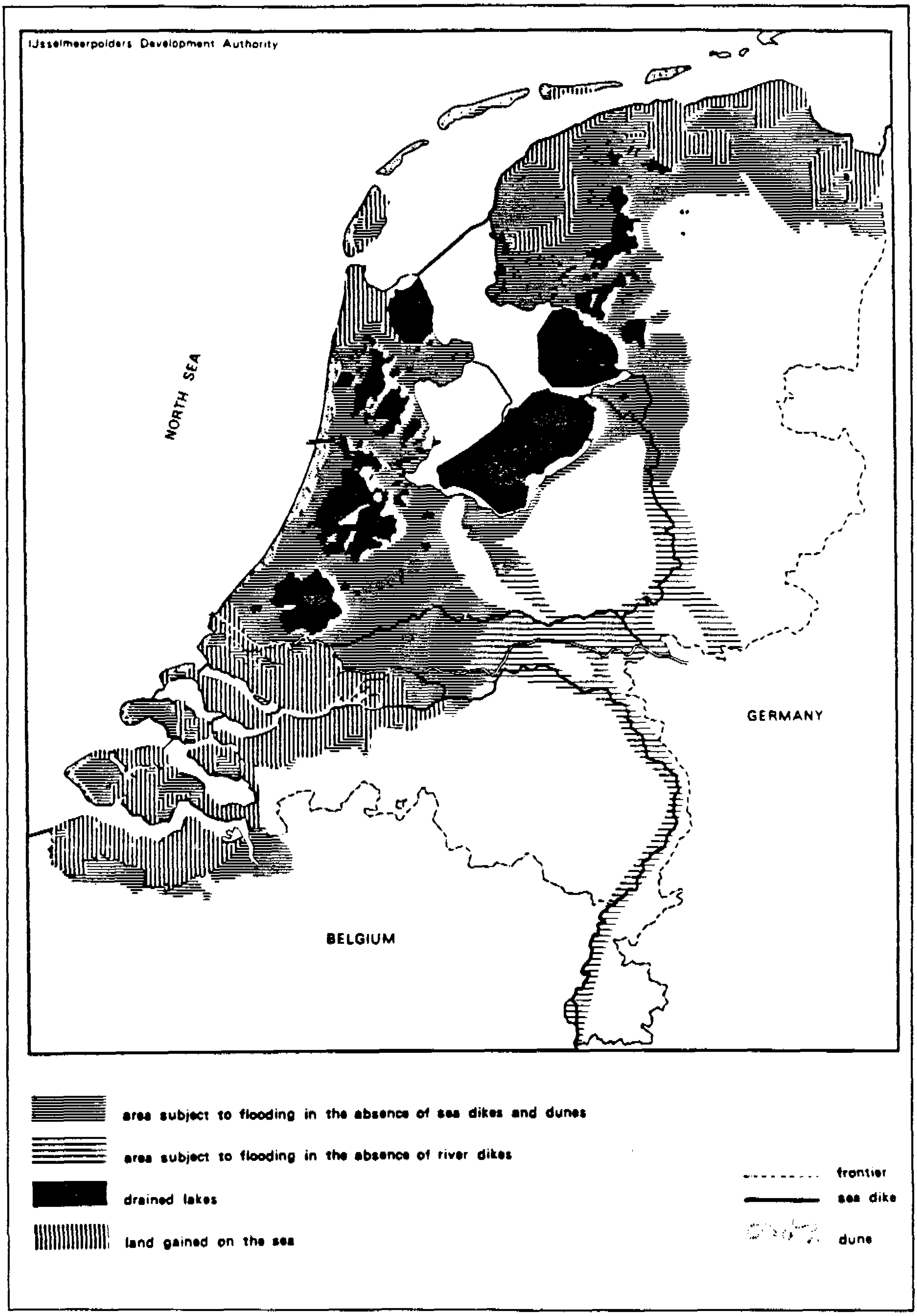


Fig. 2.2 Areas in The Netherlands protected against flooding

2.3. Irrigation and drainage

Human settlement is closely related to irrigation. A society which consists of more than 100 people requires intensive agriculture to feed those people in the society that do not produce food but which have other important tasks, such as: religious services, protection (military services), administration, manufacturing, trade, transport, etc. To feed a part of the population that does not produce requires intensive agriculture and in many cases irrigation.

The total area of cultivation in the world is about 1500 million ha. Of this total, about 250 million ha are irrigated. Normally water is diverted from a river and transported by gravity, or with the aid of pumping stations to the fields. In many cases, irrigation water is needed in the dry season, when the river flow is also low. Hence, irrigation works are often accompanied by the construction of reservoirs, in which case, high costs are involved. It should be kept in mind that **[illegible] of the larger irrigation projects in the world, which involve the construction of reservoirs, are able to pay back the costs in crop production**. The return of the costs involved in dam construction is generally paid from hydropower, or from the national budget.

In general, irrigation should be accompanied by **subsurface drainage** to avoid water logging and salinization. This is clearly illustrated by the fall of the Sumerian empire (4500-2500 BC) in present day Iraq and Iran, which was caused by desertification as a result of salinization. In these areas, as in large parts of Pakistan and India, the threat of salinization due to irrigation, is as strongly present as ever.

In addition, if no appropriate measures are taken, the drainage water from irrigated areas may cause the river from which the irrigation water has been drawn, to be polluted with salt, pesticides, herbicides and fertilizers, rendering the water useless for downstream consumption.

2.4. Flow regulation and reservoir construction

The main purpose of reservoirs is to attenuate irregularities of flow through the creation of storage. The reason why man wants to smooth out irregularities can be manifold:

- to supply water for irrigation in the dry season or during dry spells;
- to guarantee a constant supply of water for urban or industrial water consumption;
- to have a reliable source of hydropower;
- to reduce flooding hazard by smoothing out flood peaks;
- to create a reservoir for recreation and fisheries.

The five purposes mentioned require different types of operation. In the case of a reservoir for irrigation, the reservoir is filled as early as possible, to ensure that the reservoir is full at the start of the dry season. During the dry season, as much water as possible is used, while enough water is conserved to cater for a possible drought. Normally, by the end of the dry season, the reservoir will be empty except for an amount saved for the eventuality of a prolonged drought.

The water supply reservoir does not differ much from the reservoir for irrigation, except that the risk one is willing to take of running dry is smaller. This will lead to a more prudent use of water by the end of the wet season, if the rains are late.

The operation for hydropower is completely different. In the case of hydropower it is generally more beneficial to maintain the reservoir as full as possible, the whole year through, in order to maintain head. A small amount of water in a full reservoir generates as much power as a large amount of water with little head.

However, if the main purpose of the reservoir is flood control, the operation is quite different again. The reservoir should be kept as empty as possible the whole year round, to allow storage of flood water in order to release it at a moderate rate.

In reservoirs with a recreational purpose, a more or less constant water level should be maintained. For ecological purposes, a minimum amount of water is required in the reservoir for the animals to remain healthy. In some cases environmentalists require flood releases to simulate floods in downstream ecosystems.

Sometimes the sediment load of the river is so high that sedimentation control requires a special way of operating the reservoir to prevent loss of storage. These operational constraints are particularly strong in the Blue Nile (Roseris dam).

It may be clear from the above, that reservoirs that serve more than one purpose, so called multipurpose reservoirs, are not easy to operate. Many different water users will demand a different way of operating the reservoir. Hence, the water manager, also in the simple case of a single reservoir, has to take a decision in a situation of conflicting interests, taking into account multiobjectives and multiconstraints.

Multi-purpose reservoirs are normally operated based on rule curves that result in the zoning of the reservoir storage. Each zone has a certain operating rule. These operating rules are derived through systems analysis (optimization) or simulation. In Chapter 5 the theory of reservoir operation is presented, as well as models that can be used for reservoir simulation.

2.5. Water resources management in The Netherlands (TNO-CHO, 1989)

Water administration

The first settlers in the Low Countries had to protect their lives and cattle against flooding from the sea and this led to the creation of the "polders". In the Middle Ages single or groups of polders were combined to form "Water Boards", one of the earliest forms of government administration in the Netherlands, in which landowners had the right to elect their governing board. These have been followed by dike boards, storage-basin boards and purification boards. All organisations, both old and new, continue to carry out an important function in the administrative structure of the country.

In the sixteenth century the Netherlands were no more than a set of autonomous counties and duchies and only at the end of that century did the country emerge as a united political state. The political power now carried by Provinces is reflecting this historical background.

Municipalities and water boards operate with a high degree of independence, under the supervision of the provincial authorities. The central government, of course, has the supervision and final decision in many matters, and particularly in matters regarding the safety, distribution and quality of water.

The central government and the governing bodies of provinces and municipalities are so-called "general democracies". The governing boards of the water boards are elected by landowners and other functional groups.

In a country like the Netherlands it is not surprising that all levels of government have responsibilities in water management. Some 10 to 20 years ago the approximate division was that responsibility for safety and navigation was resting with the central government and the provinces and that the responsibility for water levels and internal distribution was resting with the water boards. The responsibilities of municipalities were incidental.

The government has transferred overall responsibility for water resources management to the Public Works Department (Rijkswaterstaat). Likewise, the provinces have Public Works Departments with comparable responsibilities. More recent administrative developments include the amalgamation of water boards and creation of boards with specialized responsibilities, such as: dike management and water purification (after the Pollution of Surface Waters Act came into force). The general picture, however, has always been of a very decentralized form of government with separate responsibilities, maintained by traditional codes of conduct. This system has been functioning well for many centuries. However, the modern developments of population growth, industrialization, pollution etc., call for integrated water management policies. These developments identified deficiencies in the decision making process regarding legislation and a need for a more coherent approach to planning and policy making. For example the Ministry of Environment, though not responsible for water management, is developing environmental policies which include the soil, groundwater and aquatic environment and shares with Rijkswaterstaat the responsibility to develop water quality standards. Furthermore, physical planning, environmental and water resources management are no longer separate fields of policy. This illustrates the fact that the developments of modern society have made it increasingly difficult to develop a cohesive and consistent water policy. Such a policy must balance the conflicting interests of the various sectors and regions and should be able to enhance the efficiency of water utilization.

Legislation, planning, finance.

Although there was a clear need for an integrated Water Management Act, in practice the Pollution of Surface Waters Act was considered most urgent and has been operational since 1970, followed by the Groundwater Act of 1982. A Soil Protection Act (which includes the protection of groundwater) is now actually being promoted in response to the recent discoveries of pollution from various sources. The act will be operative by the end of 1986.

A Water Management Bill with several integrating characteristics is being discussed in Parliament, but it is not fully comprehensive covering all facets of the interdisciplinary issues of planning development and management of surface and groundwater resources.

The policy instruments of these laws are generally licences and charges, but comprise also prohibitive and restrictive measures. The responsibilities are structured differently. The Pollution of Surface Waters Act divides responsibilities (dependent on the "ownership"

of the water) between government and provinces; the latter may (and in most cases do) delegate these tasks to water boards. The Groundwater Act and the Soil Protection Act delegate the major responsibility to the provinces, with a supervision at national level.
The Water Management Bill divides responsibilities between the different levels of administration and apart from licences (administration to private entities) has the new concept of "water agreements" (between authorities). Like most modern acts, those mentioned have extensive procedural securities built in with possibilities for appeal.
Planning procedures had developed into an unmanageable multitude of planning obligations. For this reason the Water Management Bill is now being reformulated to simplify the entire planning system.
The latest tendency is towards an integrated approach to water sytems (local, regional or national), meaning that all relevant aspects are taken into account. System, in this context, is not only water, but also river beds and banks, shores, and all forms of aquatic life.
Finally it should be mentioned that the method of financing water policy is subject to reconsideration. The usual financial sources are the government's general budget, the charges and levies ensuing from the various laws and the obligatory contributions to water boards. On the one hand a policy to improve the quality of life (and water!) against the odds of modern industrial society tends to become increasingly expensive. On the other hand, in managing a complicated system, it may become unclear who has responsibility for payment for a quantitative measure, exclusively aimed at qualitative improvement. For the time being these problems are unsolved in the Netherlands. They have, however, been identified and there are positive efforts to arrive at solutions. In the remainder of this chapter the topic of the water resources planning process, as a part of water resources management, will be discussed. This will include a general outline of water resources management in the Netherlands and a summary of the planning process, structure and analysis.

Table 8.1 Broad scheme of the management of groundwater and surface water by public authorities, on strategic and operational level

object of management / management level	surface water		groundwater
	national waters	regional and local waters	
strategic level	central government	provinces	provinces
operational level	central government	water boards (some provinces)	provinces

Water resources management

Why manage?

Water resources management is based on an understanding of the nature of the water resources system and of the role of public authorities.
The water resources system - as we have seen in the previous chapters - includes all elements required to produce water and water-related goods and services and consists of the following components:

1 the totality of water and its physical, chemical and biological components in and above the soil in an area considered;
2 natural elements, such as rivers and lakes;
3 the man-made physical elements, such as weirs, pipelines and canals;
4 the administrative elements, such as the existing regulations and organizational structures.

Management of this water resources system is essential in order to produce the required outputs in the most efficient way.
Water resources management can be conceived

as a production function which transforms the quantity, quality, time and location characteristics of surface water and groundwater into the quantity, quality, time and location characteristics of the desired outputs: irrigation water, water-based recreational opportunities, flood damage reduction, municipal water, industrial water, navigation opportunities, bearer of aquatic ecosystems, conditions of the soil for agricultural or building purposes.
The role of public authorities in water resources management stems from the basic objective that water resources - as a public good - should be exploited in such a way that they produce maximum net social benefit. The demands of the various users are often competitive and/or conflicting. To meet all the demands is usually impossible and therefore choices have to be made. It is the task of management to make the choices and then execute them.

Who is managing what?
In the Netherlands water resources management is a task of public authorities and not of private persons or institutions. This can be historically explained, but is also a conscious political choice. Public involvement in water resources management is found to be essential, for example in:
1 provision of collective goods, such as flood damage reduction;
2 regulating conflicts between various use categories when they apply for the same amount of water at the same time and the same location;
3 controlling the use of water from a viewpoint of general interest, such as regional development and public health.
The public authorities which are involved in water resources management are numerous. The central government is responsible for the state-managed waters (the waters of national importance, the great lakes and the territorial sea). Within the guidelines of the central government the provinces are responsible for the non statemanaged waters and the groundwater. The provinces have delegated tasks and responsibilities with respect to surface water to approximately 200 water boards. Most of them control only the quantitative aspect. Three provinces did not delegate the qualitative aspect of the surface water management. The others delegated it to some 20 to 30 water boards. The majority of the water boards control either quantitative or qualitative aspects. For the simple observer it looks like a patchwork quilt but it works! However, complications arise with other water resources management tasks, such as coastal and dike management, waterway management and the management of the underwater beds and river banks. Water resources management is closely interwoven with different areas of public responsibility, such as environmental policy and physical planning and as a result co-ordination is of utmost importance.

How is water managed?
Instruments for water resources management have been described in the previous sections. This section deals with the planning instrument, the outstanding instrument of the next decade. Planning in this chapter is considered as the formulation, evaluation and selection of strategies, that consists of a combination of the following components:
1 physical measures;
2 implementation incentives;
3 institutional arrangements.
Implementation incentives in relation to water demand encourage users to a socially desired level of water use and discharge pattern through charges, levies, permits, zoning, subsidies and regulations. A plan is the written reflection of the chosen strategy.

Planning process

Why planning?
Although the water resources system in the Netherlands is very complicated it has developed into a coherent and well ordered system. Water-related human activities and natural processes act upon each other; they are each others limiting conditions but each water system has its own individual characteristics. In order to harmonize their functions, characteristics and processes, it is necessary to manage them as a unit. This requires a continuous weighing of (human) interests and the potential of a water system. Water resources management is multi-objective. The objectives are partly complementary and partly conflicting and the trade-offs between each of them are not always clear. This demands for a careful selection of management objectives and allocation of resources in time.
Policy making and the Dutch tradition of

participation in policy making does not make a decision of today a fact tomorrow. This time-factor is another reason for planning. Planning and subsequent decision making are based on a planning process; i.e. the process of formulation, evaluation and selection of strategies, resulting in management inputs. The outcome of a planning process is sometimes an independent plan.
Although planning is not a new phenomenon, it is quite recent that the legislator has prescribed by law different kinds of plans to ensure an overall planning process for water resources management from general objectives and national policies to detailed local plans.

Planning structure
The central government, the provinces and the water boards make their own water resources management plans. At the strategic level it is a masterplan and at the operational level the plans are more detailed. In Table 8.2 the groundwater and surface water management scheme of Table 8.1 is re-presented, but completed with the plans the public authorities have to make.
In the present state of the Dutch water resources management the planning unit is both interacting and interrelated. Planning options and management strategies are increasingly developed on an interdisciplinary basis. With increasing complexities in the planning process, water resources planning is no longer the domain of engineers and economists.
Participation by others, especially in analysis, is essential and this must involve the disciplines of mathematics, law, biology, chemistry, ecology and public administration.

The frequency of plans
The present planning frequency, as laid down in acts and proposed in bills, is ten years. However in 1985 the Minister of Transport and Public Works and the Minister of Housing, Physical Planning and Environment presented to Parliament a proposal to modify the Water Management Bill so that the frequency of all the water resources management plans would be reduced to once in four years. This is very frequent considering that this kind of planning is new although ideally planning should be an iterative process and not an ad-hoc action once in four years. Major planning every ten years can be inflexible and unsuitable, for both detailed planning and for master plans. With a more frequent planning there is the possibility of extending the term by another four years.

Contents of a water resources management plan
The strategic water resources management plans are restricted to major areas which limit the operational plans. The chosen strategies and the expected financial, economic and spatial results are given in the strategic plans.

Relationship with environmental policy plans
The water resources management plans also describe their interaction with the environmental policy plan. This is important because water resources form a part of different

Table 8.2 Broad scheme of the water resources management plans to be made by public authorities, on strategic and operational level

object of management management level	surface water		groundwater
	national waters	regional and local waters	
strategic level	policy document on water management	provincial water management plan	
operational level	management plan	management plan	

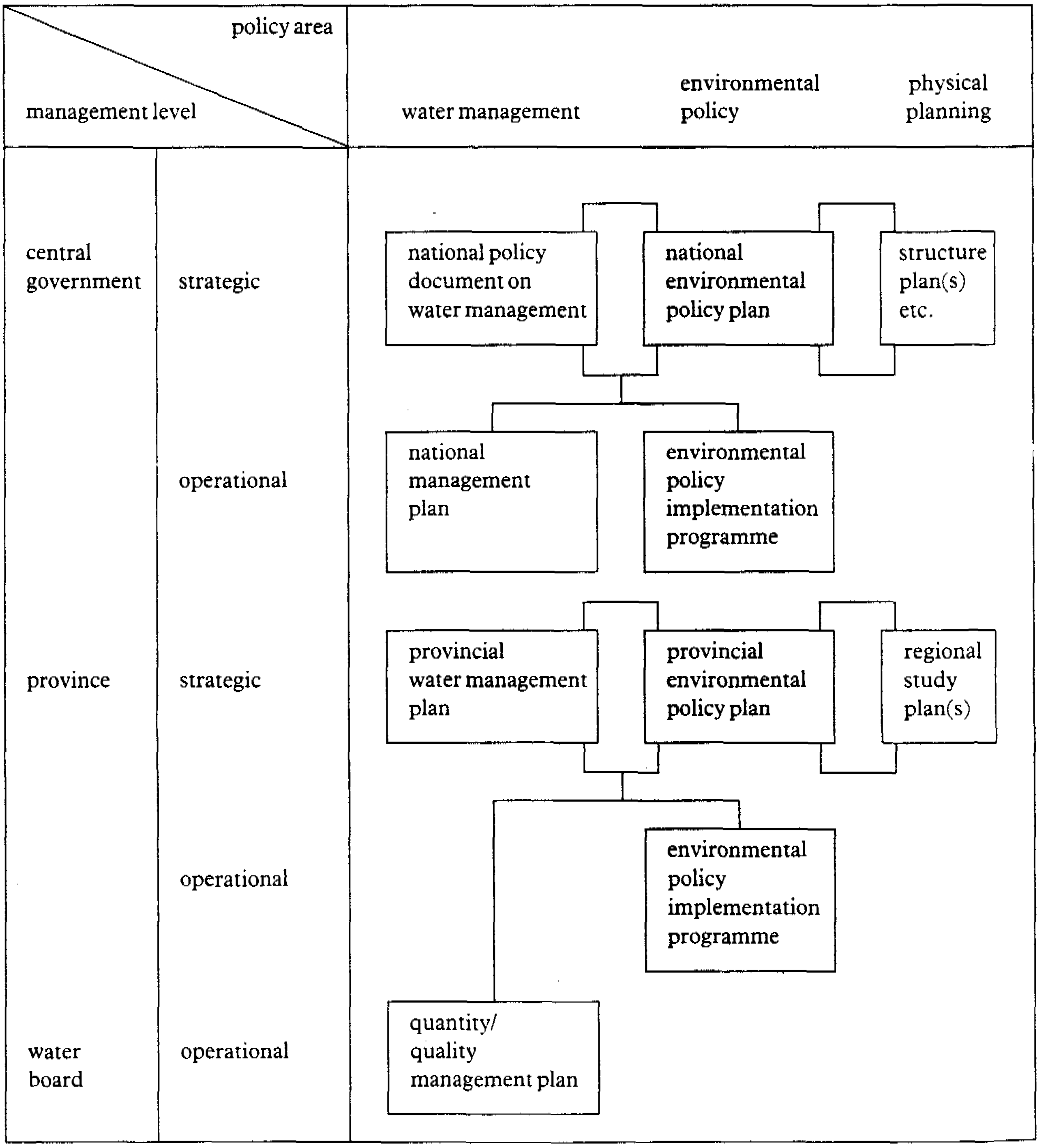
areas of public responsibility with no hierarchy. These areas are water management, environmental policy and physical planning. The structure of the environmental plans will be the same as the WRM-plans. The structure is given in Table 8.3.

Analysis in the planning process

Systems approach to water resources management

Planning anticipates and supports decision making on a particular strategy. In an integrated and complex water resources system it is essential to know the effects of particular decisions and chosen strategies. Dutch public authorities, especially at state and provincial level, have increasingly chosen a systems approach to water resources management. A systems approach carefully identifies the important issues and alternative measures related to supply, demand and institutional organizations and assesses and evaluates the impacts of formulated strategies in a way that is meaningful to the decision maker. The initial

Table 8.3 Proposed structure for the water resources planning (public water supply is excluded)



management level	policy area	water management	environmental policy	physical planning
central government	strategic	national policy document on water management	national environmental policy plan	structure plan(s) etc.
	operational	national management plan	environmental policy implementation programme	
province	strategic	provincial water management plan	provincial environmental policy plan	regional study plan(s)
	operational		environmental policy implementation programme	
water board	operational	quantity/ quality management plan		

task is to identify the questions which must be answered. Too often research is executed where it is not clear what questions are being addressed. It is therefore imperative that analysis for water resources management is management-oriented.

The planning of public water supply will not be dealt with explicitely. This sector is governed by the Water Supply Act, which forms the legal basis for e.g. drinking water standards, planning, governmental and provincial supervision. Nowadays some 100 public water supply companies are servicing about ninety-nine percent of all houses and a substantial part of the Dutch industries. Almost all public water supply companies are either a municipal service or a limited company, which shares are being held by the municipalities and the provinces concerned.

Modelling the Dutch water resources system: PAWN

The growing complexity of water resources management: i.e. the complicated structure of the problems, the many components to be considered, the aspects of space and time and the often complex relations existing between the components of the water management system, forced the Dutch analists to seek methods to help them in their tasks. More and more they were forced to make extensive use of mathematical modelling and analytical techniques.

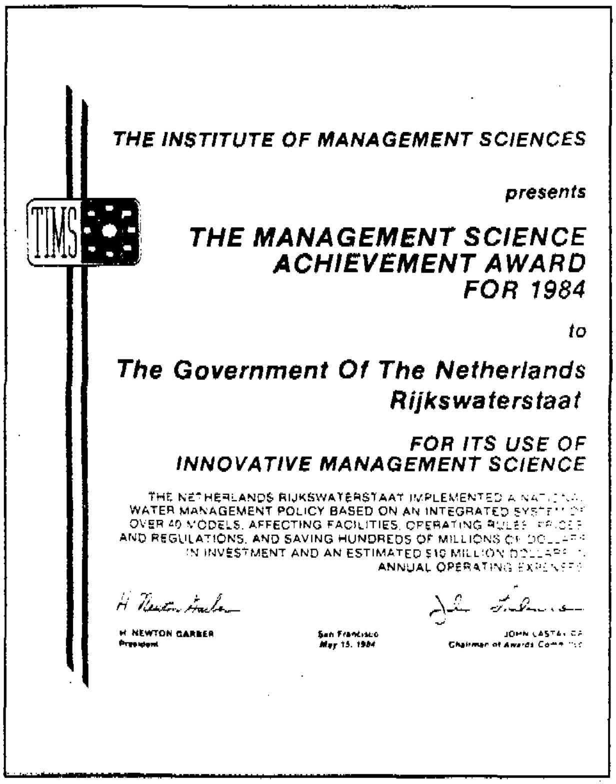
In order to carry out its planning and management task the Rijkswaterstaat must be aware of the consequences of any chosen operation. In order to meet these objectives the Rijkswaterstaat initiated the so-called PAWN (Policy Analysis of Water Management for the Netherlands). The assignment was given to the Rand Corporation (USA) and Delft Hydraulics (the Netherlands).

The objectives of PAWN were:

1 to indicate the coherence and the ranking between the various use categories related to the Dutch water management system;

2 to show the limitations of the existing water management system and suggest solutions to these problems;

3 to indicate the consequences of these solutions for all parties concerned in as many aspects as possible. Specifically PAWN was meant to provide information for the document 'De waterhuishouding van Nederland' (National Policy Document on Water Management).



THE INSTITUTE OF MANAGEMENT SCIENCES

presents

THE MANAGEMENT SCIENCE
ACHIEVEMENT AWARD
FOR 1984

to

The Government Of The Netherlands
Rijkswaterstaat

FOR ITS USE OF
INNOVATIVE MANAGEMENT SCIENCE

THE NETHERLANDS RIJKSWATERSTAAT IMPLEMENTED A NATIONAL WATER MANAGEMENT POLICY BASED ON AN INTEGRATED SYSTEM OF OVER 40 MODELS, AFFECTING FACILITIES, OPERATING RULES, PRICES AND REGULATIONS, AND SAVING HUNDREDS OF MILLIONS OF DOLLARS IN INVESTMENT AND AN ESTIMATED $10 MILLION DOLLARS IN ANNUAL OPERATING EXPENSES

H Newton Garber

H. NEWTON GARBER
President

San Francisco
May 15, 1984

JOHN CASTA[illegible]
Chairman of Awards Committee

Figure 8.1 Management Science Achievement Award 1984 for the PAWN-project

Given the fact that water management is an active process, the provision of a useful tool to be used in subsequent studies is essential. In the PAWN study approximately 40 models were built at the heart of which is the Water Distribution Model. The Institute of Management Sciences awarded the Management Science Achievement Award for 1984 to the PAWN project for its use of innovative management science (Fig. 8.1).

Regional water resources planning

Following recent legislation, analysis and planning are also taken seriously at provincial level where a surface water quality plan has been completed and a groundwater plan is being developed. Although the Water Management Bill has not been passed by Parliament, most provinces are already anticipating the strategic provincial water management plan which includes quantity and quality aspects of groundwater and surface water. There are differences between the provinces; not only in their approach, but also in identifying priorities and in implementation. To compare the results and to influence the policy of other public authorities involved in the Dutch water resources management, it is important to use the same scenarios, criteria etc., and instruments, such as compatible computer models. The Rijkswaterstaat encourages the provincial use of PAWN instruments.

In conclusion

An important step in the modernization of the Dutch water resources management is the introduction by law of the planning instrument. The coherence that characterizes the water resources systems makes the integrated approach essential.
The opportunities to support water resources management have multiplied through the development and introduction of a systems approach in water resources management.
The coming years will prove:
- whether planning will be able to live up to expectations;
- to what extent the definition of a water resources system can be broadened to make an integrated approach possible and
- whether a systems approach, the use of computer models and ongoing automation will become general practice for the public authorities involved in the Dutch water resources management.

3. WATER RESOURCES

Note: Parts of this chapter are dealt with in the lecture Principles of Hydrology. Although these topics are not presented in the lecture Water Resources Management, they have been retained in the lecture note for reasons of completeness.

3.1. Groundwater resources

Two zones can be distinguished in which water occurs in the ground:

- the saturated zone
- the unsaturated zone.

For the hydrologist both zones are important links and storage devices in the hydrological cycle. For the engineer the importance of each zone depends on his field of interest. An agricultural engineer is principally interested in the unsaturated zone, where the necessary combination of soil, air and water occurs for a plant to live. The water resources engineer is mainly interested in the groundwater which occurs and flows in the saturated zone.

The process of water entering into the ground is called **infiltration**. Downward transport of water in the unsaturated zone is called **percolation**, whereas the upward transport in the unsaturated zone is called **capillary rise**. The flow of water through saturated porous media is called **groundwater flow**. The outflow from groundwater to surface water is called **seepage**.

The type of openings (voids or pores) in which groundwater occurs is an important property of the subsurface formation. Three types are generally distinguished:

1. **Pores**, openings between individual particles as in sand and gravel. Pores are generally interconnected and allow capillary flow for which Darcy's law (see below) can be applied.
2. **Fractures**, crevices or joints in hard rock which have developed from breaking of the rock. The pores may vary from super capillary size to capillary size. Only for the latter situation application of Darcy's law is possible. Water in these fractures is known as fissure or fault water.
3. **Solution channels** and caverns in limestone (karst water), and openings resulting from gas bubbles in lava. These large openings result in a turbulent flow of groundwater which cannot be described with Darcy's law.

The **porosity** n of the subsurface formation is that part of its volume which consists of openings and pores:

$$n = \frac{V_p}{V} \tag{3.1}$$

where V_p is the pore volume and V is the total volume of the soil.

When water is drained by gravity from saturated material, only a part of the total volume is released. This portion is known as **specific yield**. The water not drained is called specific retention and the sum of specific yield and specific retention is equal to the porosity. In fine-grained material the forces that retain water against the force of gravity are high due to the small pore size. Hence, the specific retention of fine-grained material (silt or clay) is larger than of coarse material (sand or gravel).

Groundwater is the water which occurs in the saturated zone. The study of the occurrence and movement of groundwater is called groundwater hydrology or geohydrology. The hydraulic properties of a water-bearing formation are not only determined by the porosity but also by the interconnection of the pores and the pore size. In this respect the subsurface formations are classified as follows:

1. **Aquifer**, which is a water-bearing layer for which the porosity and pore size are sufficiently large to allow transport of water in appreciable quantities (e.g. sand deposits).
2. **Aquiclude** is an impermeable layer, which may contain water but is incapable of transmitting significant quantities.
3. **Aquitard** is a less permeable layer, not capable of transmitting water in a horizontal direction, but allowing considerable vertical flow (e.g. clay layer).
4. **Aquifuge** is impermeable rock neither containing nor transmitting water (e.g. granite layers).

Classification of rocks

The water transmitting properties are dominated by the type of geological formation. Rocks can be divided in three main groups:

1. Igneous rocks, which are formed at the solidification of cooling magma (e.g. granite) or volcanic material (e.g. basalt). Igneous rocks have a crystalline structure and a very low porosity (often less than 1 %). The water-bearing properties are generally very low unless an extensive jointing, fracturing and faulting is present.
2. Sedimentary rocks are formed by deposits of weathered material of pre-existing rocks. Depending on the type of transporting mechanism the following sedimentary rocks may be distinguished:
    a. Fluvial or alluvial (river) deposits, which include gravel, sand, silt and clay. These formations are characterized by stratification. The porosity varies between 20 and 60 %, but only gravel and sand show macro-pores! Due to cementing, pressure and/or temperature sand may have changed in sandstone and lime deposits into limestone. These consolidated rocks have a much lower ability to transmit water unless fractures or karst phenomena (limestone) are present.
    b. Aeolian (wind) deposits include sand and silt (loess). Often large areas are covered with relatively homogeneous material.
    c. Glacial (ice) deposits. During the Pleistocene glaciers deposited glacial till which usually is a mixture of silt, sand and clay in which pebbles and huge

boulders may be present. These deposits are in general poor water producers.

Other sedimentary rocks are named in relation to their origin, location and environmental conditions, e.g. marine (sea) deposits, organogenic deposits (from organic life), terrestrial deposits, etc.

3. Metamorphic rocks are formed from igneous or sedimentary rocks by chemical and physical processes (heat and pressure). Examples are slate, gneiss, quartzite and marble. These rocks are the poorest water producers.

Aquifers

For a description or mathematical treatment of groundwater flow the geological formation can be schematized into an aquifer system, consisting of various layers with distinct different hydraulic properties. The aquifers are simplified into one of the following types (see Fig. 3.1):

1. Unconfined aquifer (also phreatic or water-table aquifer) which consists of a pervious layer underlain by a (semi-) impervious layer. The aquifer is not completely saturated with water. The upper boundary is formed by a free water-table (phreatic surface).
2. Confined aquifer, consisting of a completely saturated pervious layer bounded by impervious layers. The water level in wells tapping those aquifers rises above the top of the pervious layer and sometimes even above soil surface (artesian wells).
3. Semi-confined or leaky aquifers consist of a completely saturated pervious layer, but the upper and/or under boundaries are semi-pervious.

The pressure of the water in an aquifer is measured with a [redacted], which is an open-ended pipe with a diameter of 3 - 10 cm. The height to which the water rises with respect to a certain reference level (e.g. the impervious base, mean sea level, etc.) is called the hydraulic head. Strictly speaking the hydraulic head measured with a piezometer applies for the location at the lower side of the pipe, but since aquifers are very pervious, this value is approximately constant over the depth of the aquifer. For unconfined aquifers the hydraulic head may be taken equal to the height of the water-table, which is known as the Dupuit-Forchheimer assumption.

Water moves from locations where the hydraulic head is high to places where the hydraulic head is low. For example, Fig. 3.1 shows that the hydraulic head in the semi-confined aquifer is below the hydraulic head (or phreatic surface) in the unconfined aquifer. Hence, water flows through the semi-pervious layer from the unconfined aquifer into the semi-confined aquifer. A perched water-table may develop during a certain time of the year when percolating soil moisture accumulates above a less pervious layer.

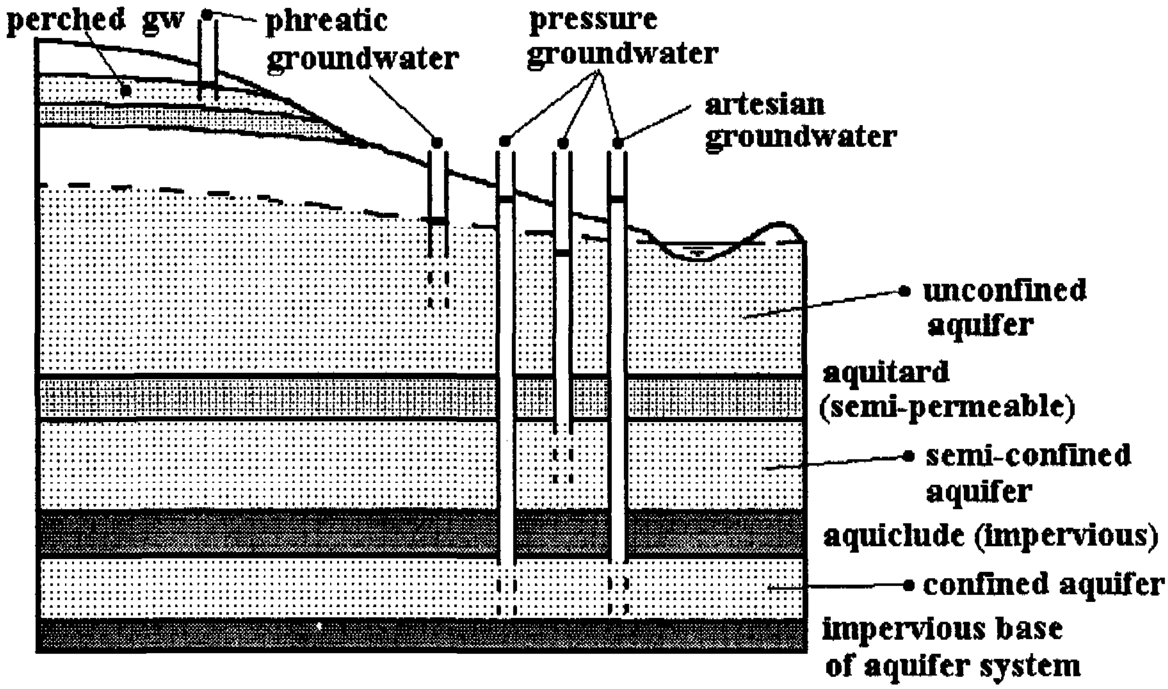


Fig. 3.1 Aquifer types

Groundwater flow

The theory on groundwater movement originates from a study by the Frenchman [redacted]y, first published in 1856. From many experiments (Fig. 3.2) he concluded that the groundwater discharge Q is proportional to the difference in hydraulic head ΔH and cross-sectional area A and inversely proportional to the length Δs, thus

$$Q = A * v = -A * k * \frac{\Delta H}{\Delta s} \tag{3.2}$$

where k, the proportionality constant, is called the hydraulic conductivity, expressed in m/d; and v is the specific discharge, also called the filter velocity.

Since the hydraulic head decreases in the direction of flow, the filter velocity has a negative sign. The actual velocity v_{act} of a fluid particle is much higher because only the effective pore space n_e is available for transport, thus

$$v_{act} = \frac{v}{n_e} \tag{3.3}$$

The effective porosity n_e is smaller than the porosity n, as the pores that do not contribute to the transport are excluded (dead-end pores). The actual velocity is important in water quality problems, to determine the transport of contaminants.

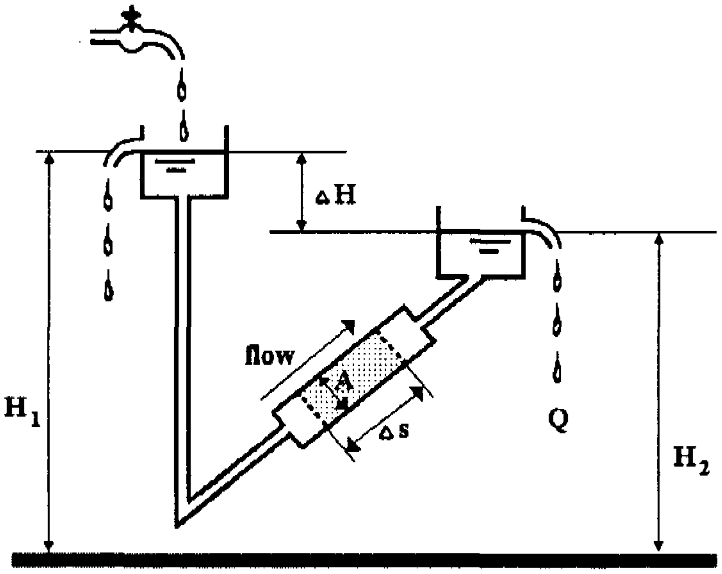


Fig. 3.2 **Experiment of Darcy**

For a detailed description of groundwater flow and groundwater recovery, reference is made to the respective lectures.

Groundwater as a storage medium

For the water resources engineer groundwater is a very important water resource for the following reasons:

- it is a reliable resource, especially in climates with a pronounced dry season
- it is a bacteriologically safe resource, provided pollution is controlled
- it is often available in situ (wide-spread occurrence)
- it may supply water at a time that surface water resources are limited
- it is not affected by evaporation loss, if deep enough
- there is a large storage capacity
- it can be easily managed

It also has a number of disadvantages:

- it is a strongly limited resource, extractable quantities are often low as compared to surface water resources
- groundwater recovery is generally expensive as a result of pumping costs
- groundwater, if phreatic, is very sensitive to pollution
- groundwater recovery may have serious impact on land subsidence or salinization

Especially in dry climates the existence of underground storage of water is of extreme importance. The water stored in the subsoil becomes available in two ways. One way is by artificial withdrawal (pumping) the other is by natural seepage to the surface water.

The latter is an important link in the hydrological cycle. Whereas in the wet season the runoff is dominated by surface runoff, in the dry season the runoff is almost entirely fed by seepage from groundwater (base flow). Thus the groundwater component acts as a reservoir which retards the runoff from the wet season rainfall and smooths out the shape of the hydrograph.

The way this outflow behaves is generally described as a linear reservoir, where outflow is considered proportional to the amount of storage:

$$Q = K\,S \tag{3.4}$$

where K is a conveyance factor of the dimension s^{-1}. Eq. 3.4 is an empirical formula which has some similarity with the Darcy equation (Eq. 3.2). In combination with the water balance equation, and ignoring the effect of rainfall P and evaporation E, Eq. 3.4 yields an exponential relation between the discharge Q and time t.

$$\frac{\Delta S}{S} = -K * \Delta t$$

hence:

$$S = S(t_0) * \exp(-K(t-t_0)) \tag{3.5}$$

and hence, using Eq.(3.4):

$$Q = Q(t_0) * \exp(-K(t-t_0)) \tag{3.6}$$

Eq. (3.6) is a useful equation for the evaluation of surface water resources in the dry season.

3.2. Surface water

Surface water resources are water resources that are visible to the eye. They are mainly the result of overland runoff of rain water, but surface water resources can also origin from groundwater. Surface water is linked to groundwater resources through the processes of infiltration (from surface water to groundwater) and seepage (from groundwater to surface water). Surface water occurs in two kinds of water bodies:

- water courses, such as rivers, canals, estuaries and streams;
- stagnant water bodies, such as lakes, reservoirs, pools, tanks, etc.

The first group of water bodies consists of conveyance links, whereas the second group consists of storage media. Together they add up to a surface water system.

The amount of water available in storage media is rather straightforward as long as a relation between pond level and storage is known. The surface water available in channels is more difficult to determine since the water flows. The water resources of a channel is defined as the total amount of water that passes through the channel over a given period of time (e.g. a year, a season, a month). In a given cross-section of a channel the total available amount of surface water runoff R is defined as the integral over time of the discharge R.

$$R = \int Q \, \mathrm{d}t \tag{3.7}$$

The discharge Q is generally determined on the basis of water level recordings in combination with a stage discharge relation curve, called a rating curve. A unique relationship between water level and river discharge is usually obtained in a stretch of the river where the river bed is stable and the flow is slow and uniform, i.e. the velocity pattern does not change in the direction of flow. Another suitable place is at a calm pool, just upstream of a rapid. Such a situation may also be created artificially in a stretch of the river (e.g. with non-uniform flow) by building a control structure (threshold) across the river bed. The rating curve established at the gauging station has to be updated regularly, because scour and sedimentation of the river bed and river banks may change the stage discharge relation, particularly after a flood.

The rating curve can often be represented adequately by an equation of the form:

$$Q = a(H-H_0)^b \tag{3.8}$$

where Q is the discharge in m^3/s, H is the water level in the river in m, H_0 is the water level at zero flow, and a and b are constants. The value of H_0 is determined by trial and error. The values of a and b are found by a least square fit using the measured data, or by a plot on logarithmic paper and the fit of a straight line (see Fig. 3.3).

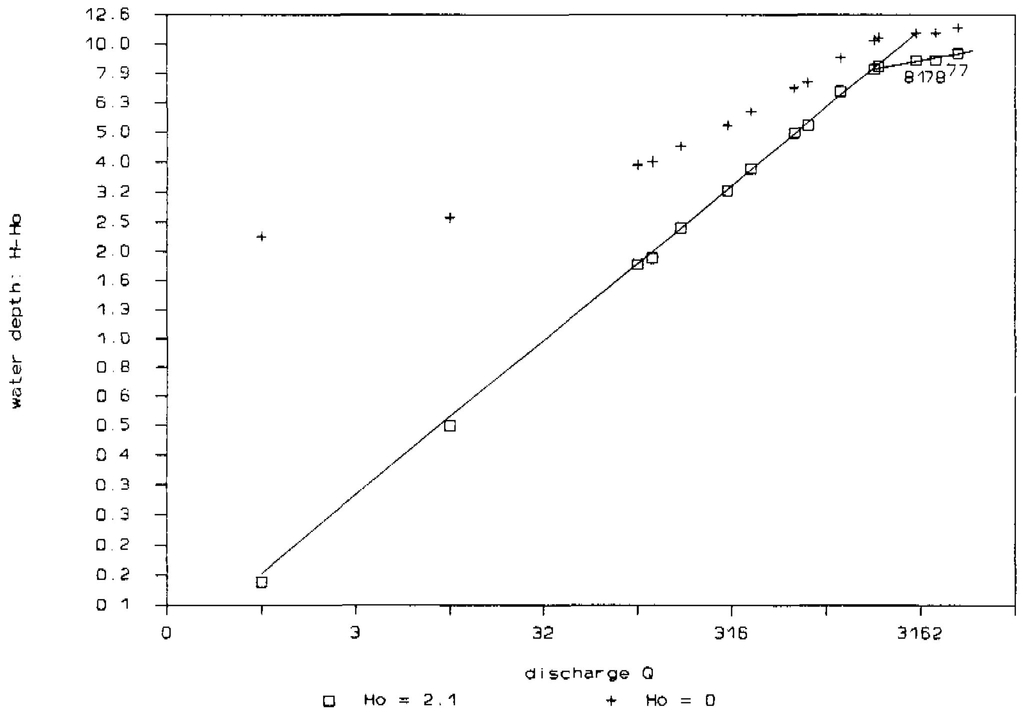


Fig. 3.3 Rating curve in Limpopo river at Sicacate

Eq. (3.8) is compatible with the Manning formula where the cross-sectional area A, and the hydraulic radius R are functions of $(H-H_0)$.

$$Q = \frac{A}{n} R^{0.667} \sqrt{S} \tag{3.9}$$

Consequently, it can be shown that the coefficient b in equation (3.8) should have a value of 1.59 in a rectangular channel, a value of 1.69 in a trapezoidal channel with 1:1

sideslopes, a value of 2.16 in a parabolic channel, and a value of 2.67 in a triangular channel.

Fig. 3.3 shows the rating curve of the Limpopo river at Sicacate; the value of b equals 1.90. The Limpopo is an intermittent river which falls dry in the dry season and can have very high flash floods during the flood season. The station of Sicacate has a value of H_0 equal to 2.1 m. In Fig. 3.3 a clear flood branch can be distinguished which is based on peak flows recorded during the floods of 1981, 1977 and 1978 in the Limpopo river. The gradient of a flood branch becomes flat as the river enters the flood plain; a small increase in water level then results in a large increase in discharge.

To illustrate the trial and error procedure in determining the value of H_0, a plot of data with $H_0=0$ has been added. It can be seen that the value of H_0 particularly affects the determination of low flow.

For the methods of measuring water levels and flows one should refer to the lectures on Hydrometry. Making use of the rating curve, a time series of water levels can be transformed into runoff series.

Water quality

The total water resources of a catchment are formed by the sum of surface water and groundwater. Both resources may not be considered separately from the water quality. Abundant water resources of poor quality are still useless for consumption. A consumer of water who pollutes the water resources system through its return flows, consumes in fact much more water than its actual consumption, as he makes the remaining water useless.

3.3. Catchment yield

Water resources engineers are primarily concerned with catchment yields and usually study hydrometric records on a monthly basis. For that purpose short duration rainfall should be aggregated. In most countries monthly rainfall values are readily available. To determine catchment runoff characteristics, a comparison should be made between rainfall and runoff. For that purpose, the monthly mean discharges are converted first to volumes per month and then to an equivalent depth per month R over the catchment area. Rainfall *P* and runoff *R* being in the same units (e.g. in mm/month) may then be compared.

A typical monthly rainfall pattern is shown in Fig. 6.5 for the catchment of the Cunapo river in Trinidad. The monthly runoff has been plotted on the same graph. Fig. 6.6 shows the difference between *R* and *P*, which partly consists of evaporation losses *E* (including interception, open water evaporation, bare soil evaporation and transpiration) and partly is caused by storage. On a monthly basis one can write:

$$R = P - E - \Delta S/\Delta t \qquad (3.10)$$

The presence of the Evaporation and the Storage term makes it difficult to establish a straightforward relation between *R* and *P*. The problem is further complicated in those regions of the world that have distinctive rainy and dry seasons. In those regions the different situation of storage and evaporation in the wet and dry season make it difficult to establish a direct relation.

Fig. 3.6 shows the plot of monthly rainfall *P* against monthly runoff *R* for a period of four years in the Cunapo catchment in Trinidad. The plots are indicated by a number which signifies the number of the month. The following conclusions can be drawn from studying the graph.

- There appears to be a clear threshold rainfall below which no runoff takes place. The threshold would incorporate such effects as interception, replenishment of soil moisture deficit, evapotranspiration, surface detention, and open water evaporation.

- It can be seen that the same amount of rainfall gives considerably more runoff at the end of the rainy season than at the start of the rainy season. The months with the numbers 10, 11 and 12 are at the end of the rainy season, whereas the rainy season begins (depending on the year) in the months of May to July. At the start of the rainy season the contribution of seepage to runoff is minimal, the groundwater storage is virtually empty and the amount to be replenished is considerable; the value of $\Delta S/\Delta t$ in Eq.(3.10) is thus positive, reducing the runoff *R*. At the end of the rainy season the reverse occurs.

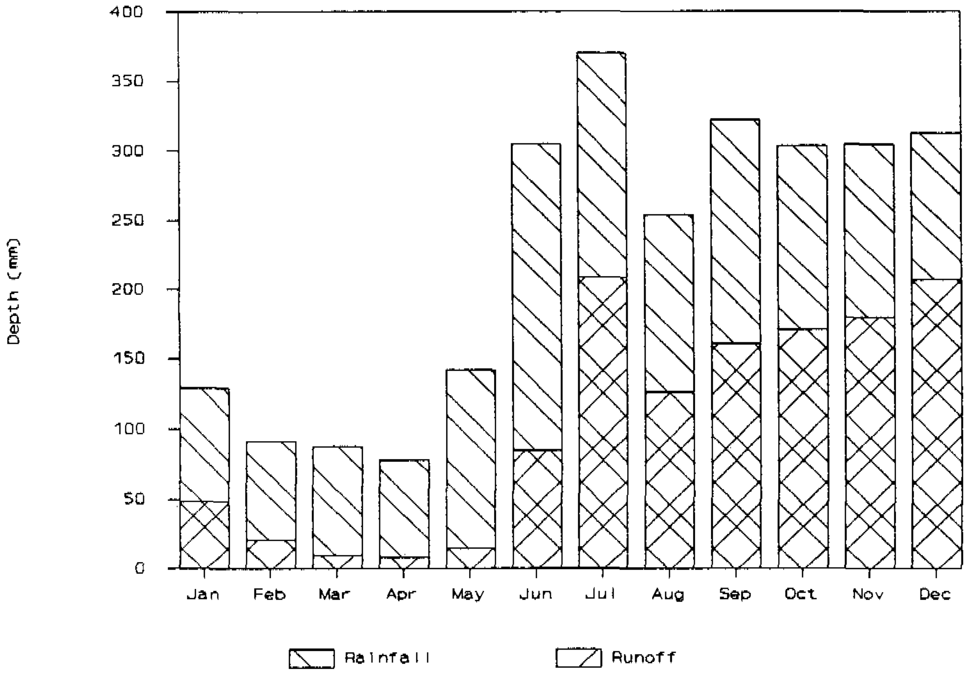


Fig. 3.4 Monthly mean rainfall and runoff in the Cunapo catchment

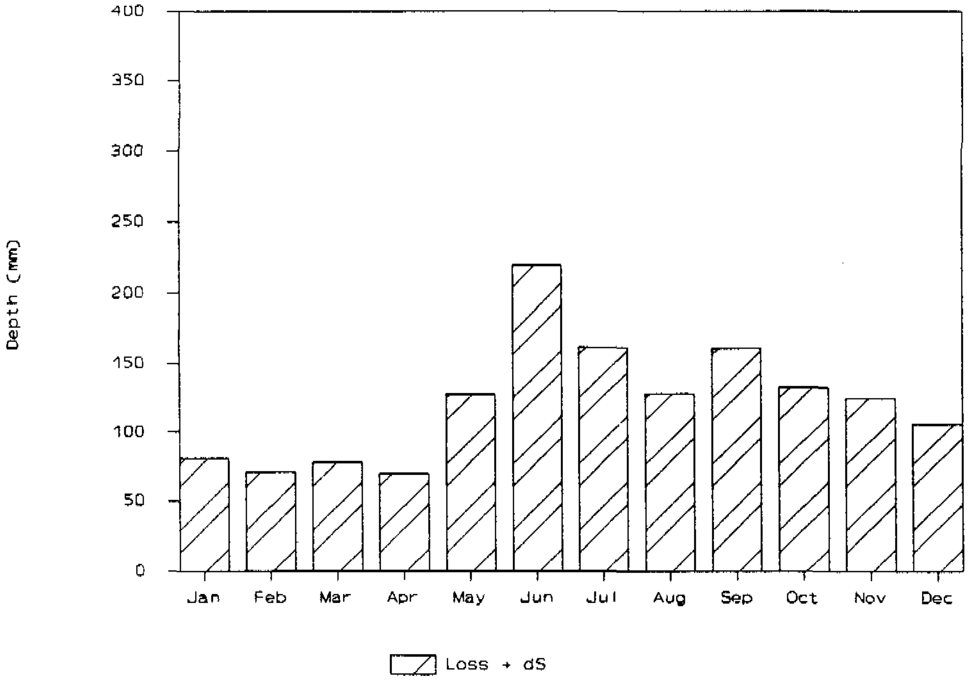


Fig. 3.5 Mean monthly losses and change in storage in the Cunapo catchment

The threshold rainfall is quite in agreement with Eq.(3.10) and has more physical meaning than the commonly used proportional losses. Proportional losses are rather a result of averaging. They can be derived from the fact that a high amount of monthly rainfall is liable to have occurred during a large number of rainy days, so that threshold losses like interception and open water evaporation have occurred a corresponding number of times.

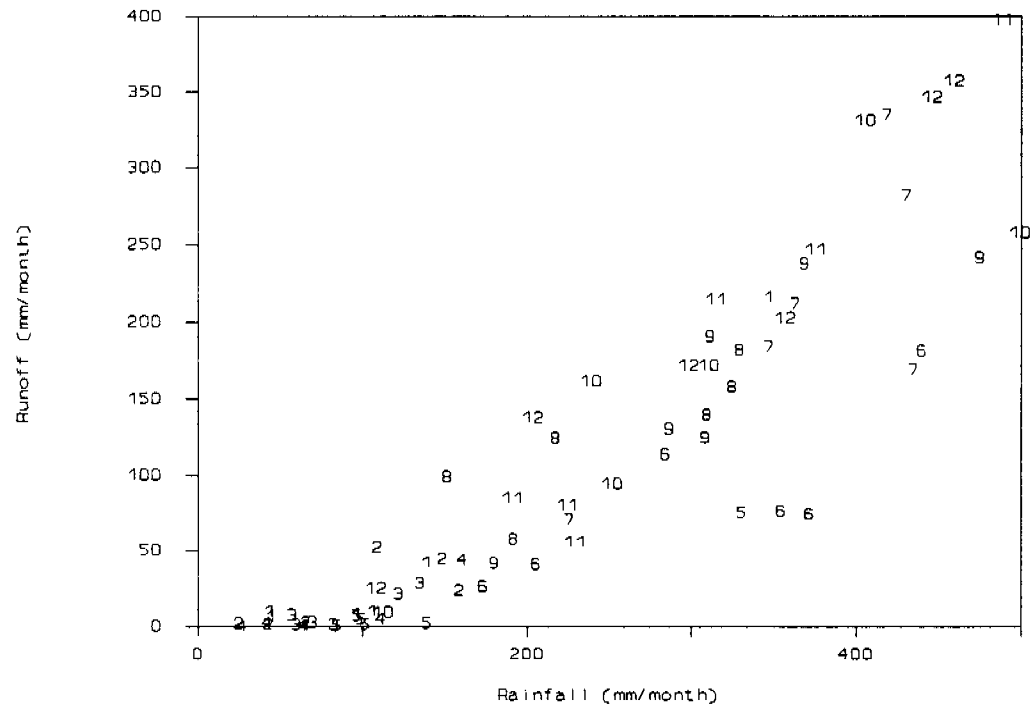


Fig. 3.6 Rainfall plotted versus runoff in the Cunapo river basin

By taking into account the threshold loss T and the groundwater storage S, a relation can be obtained between R and P. The following model, which can easily be made in a spreadsheet, has been developed for that purpose.

Moving average model for monthly runoff using threshold losses

As the amount of storage available during a particular month depends on the amount of rainfall in the previous months, a relation is sought that relates the runoff in a particular month to the rainfall in the month itself and the previous months. A simple linear backward relation is used:

$$R_t = a + b_0(P_t - T) + b_1(P_{t-1} - T) + b_2(P_{t-2} - T) + \dots \tag{3.11}$$

under the condition that if $(P_{t-i} - T) < 0$, then $(P_{t-i} - T) = 0$

T is the threshold loss on a monthly basis, b_i is the coefficient that determines the contribution of the effective rainfall in month t-i to the runoff in month t (proportional loss); and a is a coefficient which should be zero if the full set of rainfall contributions and losses were taken into account.

In matrix notation Eq. (3.11) reads:

$$R_t = \mathbf{B}(\mathbf{P-T}) + a \qquad (3.12)$$

where R_t is a scalar, the runoff in month t, **B** is an n by 1 matrix containing the coefficients b_i and (**P-T**) is a state vector of 1 by n containing the effective monthly precipitation values of the present and previous months. The value n-1 determines the memory of the system. Obviously n should never be more than 12, to avoid spurious correlation, but in practice n is seldom more than 6 to 7.

The effective runoff coefficient C, on a water year basis, is defined as:

$$C = \frac{R}{P-T} \qquad (3.13)$$

where P and R are the annual rainfall and runoff on a water year basis. It can be seen from comparison of Eq.'s (3.12) and (3.13) that (if the coefficient a equals zero) the sum of the coefficients in **B** should equal the effective runoff coefficient C:

$$\Sigma(b_i) \approx C \qquad (6.8)$$

meaning that the total amount of runoff that a certain net rainfall generates is the sum of all the components over n months. Obviously C should not be larger than unity.

The coefficients of **B** are determined through multiple linear regression. For the example of Fig. 3.6 these results are presented in Table 3.1. Although the best correlation is obtained with a memory of 5 months, the most significant step is made by including the first month back. Moreover it can be seen that the correlation substantially improves by taking into account the threshold rainfall. Fig. 3.7 shows the comparison between computed and measured runoff for a threshold value T = 120 mm/month.

Threshold value: T = 0
Average effective runoff coefficient: C = 0.45

	t	t-1	t-2	t-3	t-4	t-5	t-6
R^2	0.74	0.75	0.76	0.76	0.77	0.78	0.81
Se	53.5	53.5	52.8	52.9	51.5	51.2	47.5

Threshold value: T = 120
Average effective runoff coefficient: C = 0.85

	t	t-1	t-2	t-3	t-4	t-5	t-6
R^2	0.83	0.88	0.88	0.89	0.89	0.90	0.90
Se	43.7	37.0	37.1	36.1	36.1	35.0	35.1

Result best regression:

Memory: i = 5 months
constant: a = -30

	b_0	b_1	b_2	b_3	b_4	b_5
Coefficients:	0.75	0.21	-0.0	0.05	0.01	0.09

Table 3.1 Summary of correlation Cunapo catchment

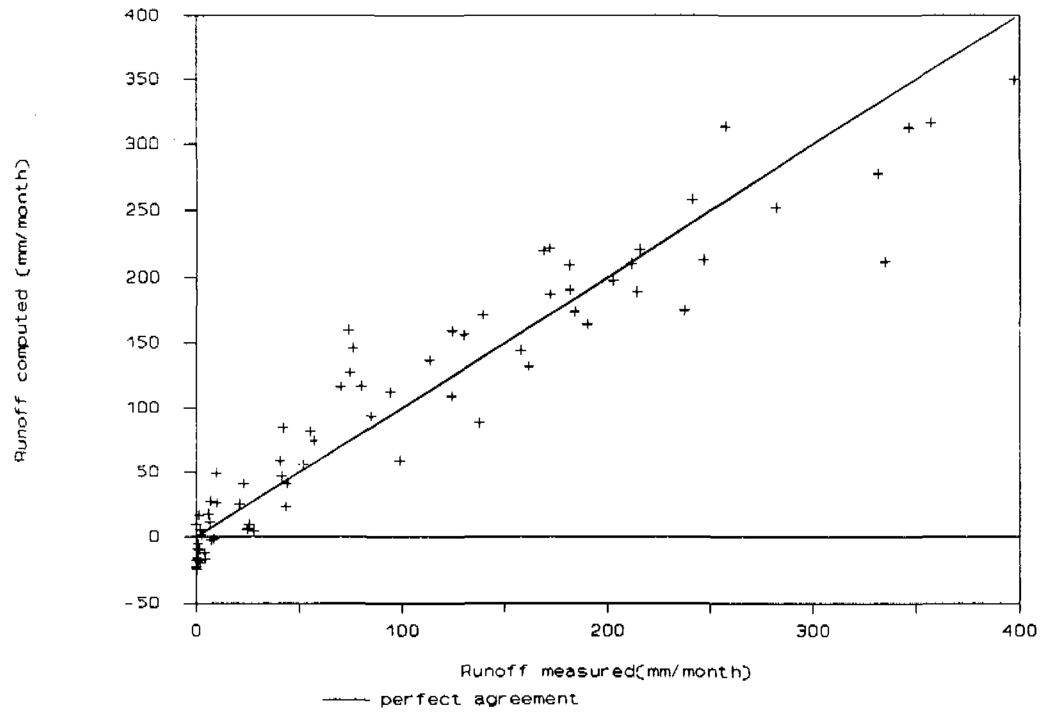


Fig. 3.7 Measured versus computed runoff in the Cunapo catchment (T=120)

3.4. Integrated water resources

The addition of the word integrated to the term water resources refers to three aspects:

- location of the resource: e.g. upstream, downstream, basin, sub-basin
- type of the resource: groundwater, surface water, rainfall harvesting, dew harvesting
- quality: water of bad quality is no resource unless it is treated.

It is not correct to consider the different aspects of water resources in isolation. The integration of location, type and quality is a necessary condition for water resources management.

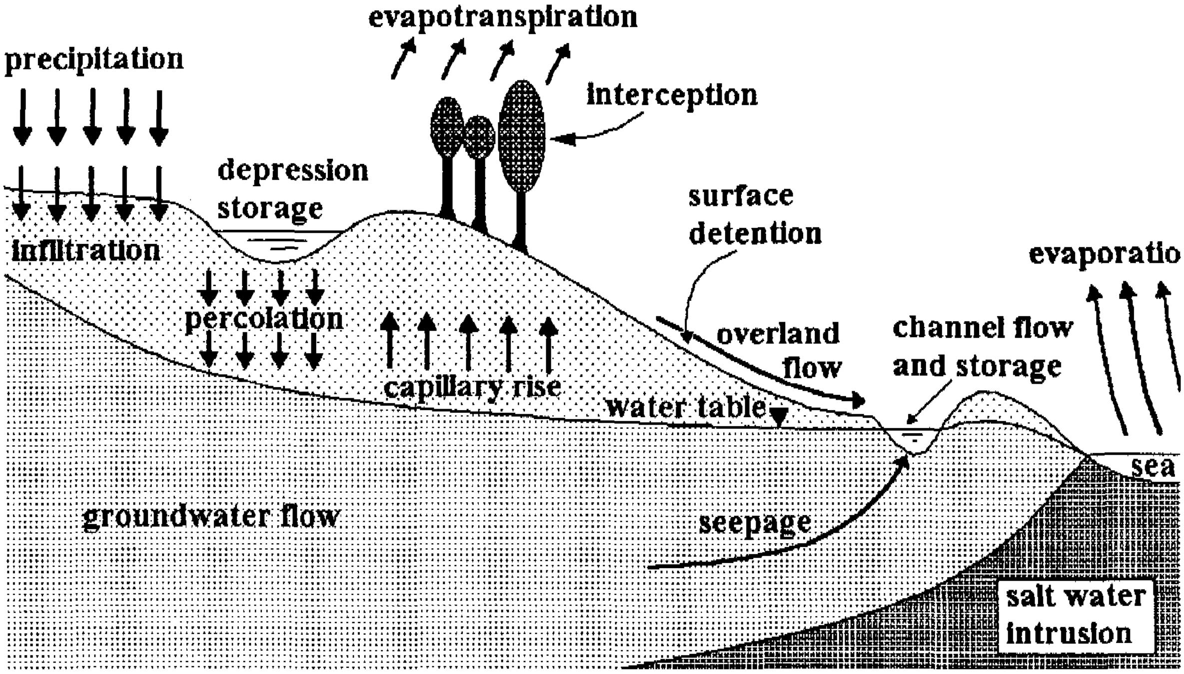


Fig. 3.8. Descriptive representation of the hydrological cycle

Fig. 3.8 shows a picture of the well known hydrological cycle. In this figure, the direct link between groundwater and surface water is apparent. If we add the aspect of water quality, the picture of integrated water resources is complete.

For Integrated Water Resources Management (IWRM), however, further integration is needed with regard to institutional, economical, financial, legal, environmental and social aspects (as mentioned in Chapter 1). But with regard to the physical aspects of water we can limit ourselves to location, type and quality.

Water balance

In the field of hydrology the budget idea is widely used. Water balances are based on the principle of continuity. This can be expressed with the equation:

$$I(t)-O(t) = \frac{\Delta S}{\Delta t} \tag{3.15}$$

where I is the inflow in $[L^3/T]$, O is the outflow in $[L^3/T]$, and $\Delta S/\Delta t$ is the rate of change in storage over a finite time step in $[L^3/T]$ of the considered control volume in the system. The equation holds for a specific period of time and may be applied to any given system provided that the boundaries are well defined. Other names for the water balance equation are Storage Equation, Continuity Equation and Law of Conservation of Mass.

Several types of water balances can be distinguished, like:

- the water balance of the earth surface;
- the water balance of a drainage basin;
- the water balance of the world oceans;
- the water balance of the water diversion cycle (human interference);
- the water balance of a local area like a city, a forest, or a polder.

The water balance of the earth surface

The water balance of the earth surface is composed by all the different water balances that can be distinguished. Data constituting the occurrence of water on earth are given in the table 3.2, 3.3, and 3.4. The water balance of the interaction between the earth surface and the world oceans and seas is given in Table 3.5.

	Area in 10^6 Mm^2	Area in %
Water surfaces	361	71
Continents	149	29
Total	510	100

Table 3.2 Earth surfaces (Baumgartner, 1972).

	Area in 10^6 Mm^2	Area in % of total	Area in % of continents
Deserts	52	10	35
Forests	44	9	30*
Grasslands	26	5	17
Arable lands	14	3	9
Polar regions	13	2	9
Oceans	361	71	

* in 1993 this number may be significantly lower

Table 3.3 Earth land use (Baumgartner, 1972)

Water Occurrence	10^3 Gm^3	Amount of water	
		% of water	% of fresh water
World Oceans	1300000	97	
Salt lakes/seas	100	0.008	
Polar ice	28500	2.14	77.6
Atmospheric water	12	0.001	0.035
Water in organisms	1	0.000	0.003
Fresh lakes	123	0.009	0.335
Water courses	1	0.000	0.003
Unsaturated zone	65	0.005	0.18
Saturated zone	8000	0.60	21.8
Total fresh water	36700	2.77	100
Total water	1337000	100	

Table 3.4 Amount of water on earth according to the survey conducted within the international geophysical year (Holy, 1982)

Region	Area	Precipitation		Evaporation		Runoff	
	10^6 Mm^2	m	10^3 Gm^3	m	10^3 Gm^3	m	10^3 Gm^3
Oceans	361	1.12	403	1.25	449	-0.13	-46
Continents	149	0.72	107	0.41	61	0.31	46

Table 3.5 Annual water balance of the earth according to the international geophysical year (Holy 1982)

Ocean	surface area	P-E	land runoff	ocean exchange	P-E	land runoff	ocean exchange	
	10^{12} m^2	mm	mm	mm	10^{12} m^3	10^{12} m^3	10^{12} m^3	m^3/s
Arctic	8.5	44	307	351	0.4	2.6	3	94544
Atlantic	98	-372	197	-175	-36.5	19.3	-17	-543466
Indian	77.7	-251	72	-179	-19.5	5.6	-14	-440739
Pacific	176.9	90	69	159	15.9	12.2	28	891318

Table 3.6 Annual water balance of World Oceans

The water balance of the oceans

Table 3.6 shows a very interesting result of applying the water balance to the world oceans, particularly with regard to the exchange of water between oceans. It can be concluded from Table 3.6 that from the Pacific about 440 000 m^3/s flows to the Indian Ocean and an equal amount to the Atlantic. An additional 94 500 m^3/s flows directly from the Arctic to the Atlantic. This water balance explains why there is an average flow from the Pacific to the Indian Ocean through the Indonesian Archipelago.

Anthropogenic contribution to seas level rise

In a recent article in Nature, Sahagian et al. (1994) drew very interesting conclusions from the information presented in Tables 3.4 and 3.5. **They demonstrated that massive withdrawal of fossil water from aquifers has an enormous potential for sea level rise, and that the groundwater withdrawal to date already explains 30% of the existing seas level** rise. A simple computation shows that the total amount of groundwater in the saturated zone corresponds with 8000/361=22 m sea level rise. Table 3.7 and Fig. 3.9 show the details of their findings.

Water balance of a drainage basin

The water balance is often applied to a river basin. A drainage basin (also called watershed, catchment, or drainage basin) is the area contributing to the discharge at a particular river cross-section. The size of the catchment increases if the point selected as outlet moves downstream. If no water moves across the catchment boundary indicated by the broken line, the input equals the precipitation P while the output comprises the evapotranspiration E and the river discharge Q at the outlet of the catchment. Hence, the water balance may be written as:

$$(P-E)*A - Q = \frac{\Delta S}{\Delta t} \tag{3.16}$$

where ΔS is the change of storage over the time step Δt, and A is the surface area of the catchment upstream of the station where Q has been measured.

ΔS, **the change in the amount of water stored in the catchment, is difficult to measure.** However, if the 'account period' for which the water balance is established is taken sufficiently long, the effect of the storage term becomes less important, as precipitation and evapotranspiration accumulate while storage varies within a certain range. When computing the storage equation for annual periods, the beginning of the balance period is preferably chosen at a time that the amount of water in store is expected not to vary much for each successive year. These annual periods, which do not necessarily coincide with the calender years, are known as hydrologic - or water years. The storage equation is especially useful to study the effect of a change in the hydrologic cycle.

Water reservoir	Total volume removable ($\times 10^{12}$ m^3)	Sea level equivalent (cm)	Present net extraction rate ($\times 10^{10}$ m^3 yr^{-1})	Sea level rise rate (mm yr^{-1})	Projected sea level change next 50 yr (mm)	Estimated sea level change to date (mm)
High Plains	4.0	1.1	1.2	0.03	1.6	1.1
SW US	3.0	0.83	1.0	0.03	1.5	0.92
California	10.0	2.7	1.3	0.04	1.9	1.2
Sahara	600	167.0	1.0	0.03	1.4	0.56
Arabia	500	140.0	1.6	0.04	2.2	0.89
Aral (lake)						
1960	1.1	0.3	2.7	0.08	3.0	2.2
1990	0.3	0.08				
Aral (ground water)	2.2	0.6	3.7	0.1	5.1	3.1
Caspian (lake)	56.0	15.4	0.77	0.02	1.1	1.3
Caspian (grdwtr)	220.0	61.2	0.47	0.01	0.65	0.78
Sahel (soil water)	0.1	0.03	0.34	0.01	0.5	0.28
Deforestation	3.3	0.9	4.9	0.14	6.8	3.4
Wetland reduction	8.6	2.4	0.2	0.006	0.3	1.3
Dams	−1.9	−0.52	—	—	—	−5.2
Total	1,406.7	392.1	19.2	0.54	26.1	11.8

'Total volume removable' is the amount of water that could be withdrawn economically from each aquifer with present-day technology. Methods of volume estimation vary from one aquifer (and economic condition) to another, so these figures should be considered as rough approximations. 'Sea level equivalent' is the amount that eustatic sea level would rise if the total removable volume were added to the oceans with an area of 3.6×10^{14} m^2. *'Present net extraction rate' is the rate of water removal after accounting for recharge rates of* 6.75×10^9, 1.05×10^9 *and* 7.8×10^8 m^3 yr^{-1} for the High Plains, Southwest US and California aquifers, respectively. Saharan and Arabian aquifers are not recharging significantly. 'Projected sea level change' is the volume of water that would be withdrawn in 50 yr if the extraction rate remained the same as it is at present. 'Sea level change to date' is the contribution of each aquifer to the twentieth-century sea level rise. For most cases, this was calculated by assuming a linear increase in extraction rate from 0 to the present rate. The increase is assumed to have begun in 1930 for American aquifers, 1950 for Saharan and Arabian aquifers, 1960 for Sahel desertification and 1940 for deforestation. Deforestation figures include only losses of tropical forests. Wetland reduction includes the total global wetland area in total removable volume, but the rates and projections include only the loss of wetlands in the United States. If the rate of reduction in the rest of the world is equal to the US rate, these figures should be doubled, and thus represent a very conservative estimate. The Aral and Caspian histories are well recorded by their fluctuating levels. We assume a specific yield of 0.2 in the sands in the surrounding desert, over an area of ~5 times the area of the lake itself for the Aral, and 3 times the area for the Caspian. At the present rate of reduction, the Aral will be gone in ~20 yr. The negative values for dammed reservoirs reflect excess water storage on land, assuming all reservoirs are constantly filled to capacity. The river damming programs of the 1960s and early 1970s have tapered off.

Table 3.6 Antropogenic contributions to sea level rise (source: Sahagian et al., 1994)

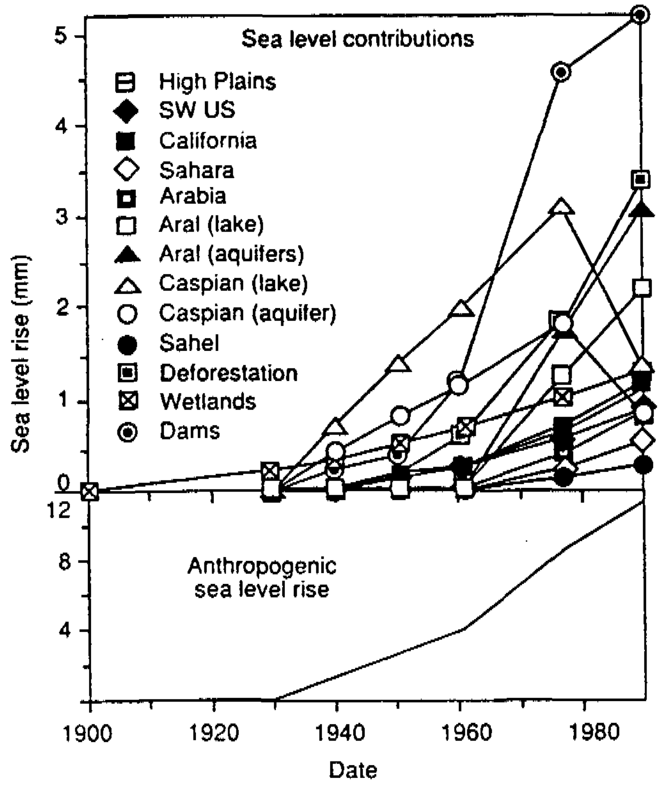


Fig. 3.9 Antropogenic contributions to sea level rise (source: Sahagian et al. 1994)

To give an impression of the difference in the water balances of drainage basins, the water balances for the basins of some great rivers are given in Table 3.8.

River	Catchment size	Rainfall		Evapo-transpiration		Runoff		Runoff Coefficient
	10^3 Mm^2	mm	10^9m^3	mm	10^9m^3	mm	10^9m^3	%
Nile	2803	220	620	190	534	30	86	14
Mississippi	3924	800	3100	654	2540	142	558	18
Parana	975	1000	980	625	610	382	372	38
Orinoco	850	1330	1150	420	355	935	795	70
Mekong	646	1500	970	1000	645	382	325	34
Amur	1730	450	780	265	455	188	325	42
Lena	2430	350	850	140	335	212	514	60
Yenisei	2440	450	1100	220	540	230	561	51
Ob	2950	450	1350	325	965	131	385	29
Rhine	200	850	170	500	100	350	70	41

Table 3.8 Indicative average annual water balances for the drainage basins of some of the great rivers

The water balance as a result of human interference

Attempts have been made to incorporate the interference of man in the hydrological cycle through the introduction of the water diversion cycle, which includes water withdrawal and water drainage. This diversion cycle is exerting significant influence on the terrestrial water cycle, especially in highly economically developed regions with a dense population (See Fig. 3.10)

The water diversion cycle including human interference results in the following water balance equation (Rodda and Matalas, 1987).

$$P = E + A + R$$

$$A = I_s + I_g - D \tag{3.17}$$

In which:
P = precipitation on the ground surface
E = evapotranspiration from the ground surface
A = net water consumption due to water use
R = runoff from land to ocean
I_s = intake of water from surface runoff
I_g = intake of groundwater
D = drainage of waste water

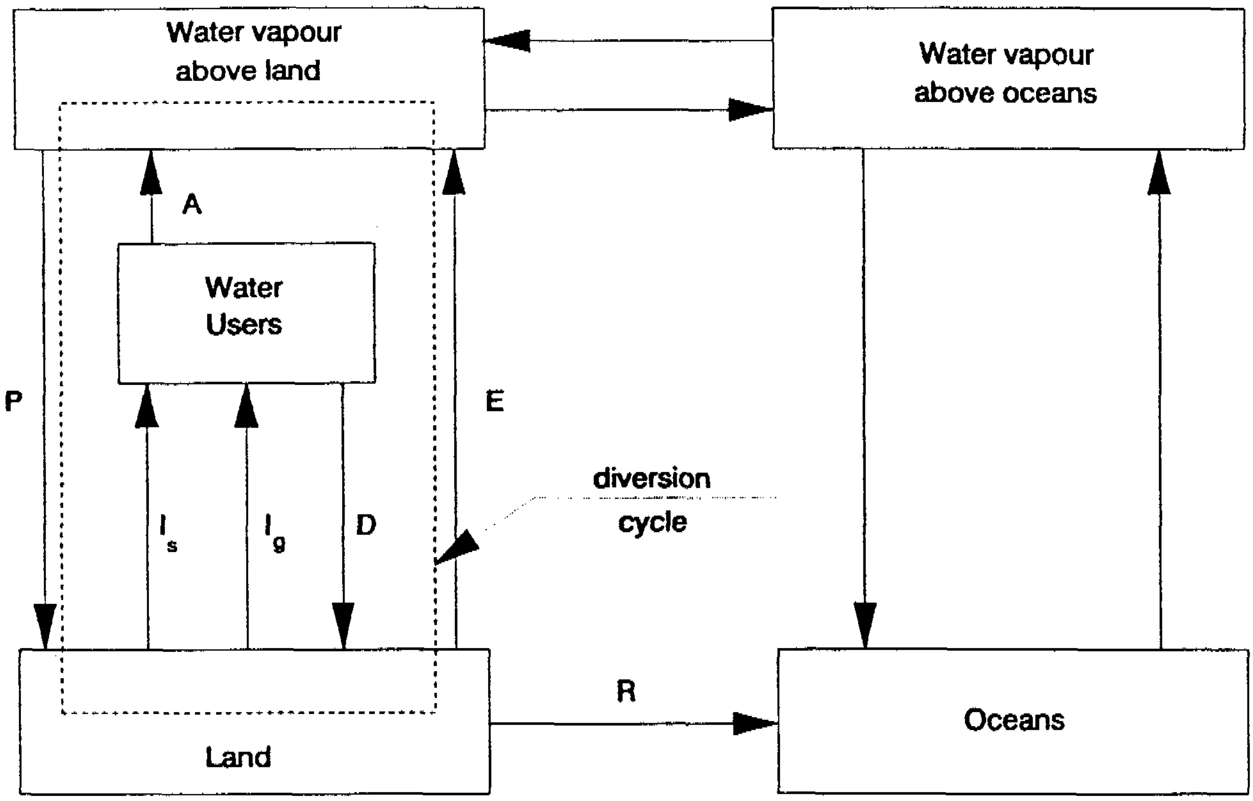


Fig 3.10 Scheme of the hydrological cycle with the diversion cycle (after Rodda and Matalas, 1987)

3.5. Is evaporation a loss?

In most water balances, evaporation is considered a loss. Hydrological engineers who are asked to determine surface runoff, consider evaporation a loss. Water resources engineers who design reservoirs, consider evaporation from the reservoir a loss. For agricultural engineers, however, it depends on where evaporation occurs, whether it is considered a loss or not. If it refers to the water evaporated by the crop (transpiration), then evaporation is not a loss, it is the use of the water for the intended purpose. If it refers to the evaporation from canals or from spill, then evaporation is considered a loss which reduces the irrigation efficiency.

However, there is a situation where evaporation, whether intentional or non-intentional, is not a loss. This is in the case of large continents where water vapour is transported inland by a prevailing wind. Such a situation occurs, for instance, in West Africa. Moist air is transported inland by the monsoon. Most of the air moisture precipitates on the tropical rainforests near the coast. Further inland it becomes dryer. Further inland, beyond the rainforest belt, lies the Savanna woodland, followed by the Sahel and the desert.

It has been shown by Savenije and Hall (1994) and Savenije (1995a) that the rainfall that falls on the Sahel, for a very large portion (more than 90%), consists of water that has evaporated from the areas nearer to the coast. On average, a moisture particle requires 250 km (recycling length) to reach the earth surface, after which it can be recycled (through evapotranspiration) or disappear from the system through runoff or deep percolation. Recycling of moisture through evapotranspiration sustains the rain that falls in the Sahel.

Evaporation in the rainforest and the savanna woodlands, hence, is essential for the climate in the Sahel. In this case, evaporation is not a loss, it is the most important source of rainfall further inland.

On a river basin scale, it can be shown that the portion of the rainfall that is recycled from evapotranspiration approaches 1-C_R (where C_R is the runoff coefficient), and that the average number of times that a water particle is recycled approaches 1/C_R (Savenije, 1995b). In semi-arid river basins, where a runoff coefficient of 10% is not abnormal, this implied that 90% of the rainfall stems from recycled moisture and that, on average, a water particle returns ten times to the earth surface as rainfall. It follows that in semi-arid areas it is essential to maintain evaporating capacity.

In the Sahel, evaporation is not a loss. What is a loss to the system is surface runoff. Not only does it extract water from the system, it also carries nutrients and soil particles. Reduction of runoff and, hence, increase of local evaporation is an important element of water harvesting. Measures that can be used to decrease runoff are reforestation, erosion control, watershed management, restoration of infiltration capacity, forest-fire prevention and prevention of over-grazing.

4. WATER DEMAND

4.1. General

Man uses water resources in many ways. All water users, through their consumption or use, affect the state of the water resource system, in one way or another. However, the degree at which the different water uses affect the state of the system are quite different. Where some types of water uses require large amounts of water of moderate quality (e.g. for irrigation), others require only small quantities of a very high quality (e.g. for domestic water supply), and again others just make use of it without really influencing the state of the resource (e.g. for fisheries). The most common types of water use are:

- Hydropower
- Irrigation
- Domestic and public use
- Rural use (domestic and livestock)
- Industrial use
- Commercial use
- Cooling
- Waste and wastewater disposal
- Navigation
- Recreation
- Fisheries
- Wildlife and nature preservation

A distinction is made between withdrawal use and nonwithdrawal use. Withdrawal uses are from diversion of water from groundwater or surface water sources such as hydropower, irrigation, domestic, rural, industrial and commercial water supply and cooling. Nonwithdrawal uses are on-site uses such as navigation, fisheries, wildlife, water-based recreation, and wastewater disposal by dilution.

Withdrawal use is subdivided into consumptive and nonconsumptive use. Consumptive use is the portion of the water withdrawn that is no longer available for further use because of evaporation, transpiration, incorporation into manufactured products and crops, or use by human beings and livestock. The terms "consumption" and "demand" are often confused. This is not correct, since only a portion of the water demand is actually consumed, i.e. lost from the water resource system.

One could argue that certain nonwithdrawal uses are consumptive uses as well. Wastewater disposal and pollution, for instance, may turn the available water resources worthless for further use, which is the same as withdrawing the water from the water resource system.

There is a generally increasing demand for water throughout the world. As populations and living standards grow and economies develop, the demands made upon water resources continue to increase. But if the demand grows, then what about the supply; can the supply continue growing as well? Clearly the basic resource does not alter; the total amount of water entering the hydrological cycle is limited, and hence the amount we can withdraw from it. Already in many developing regions, much of the demand is unsatisfied because of inadequate water supplies. Can technology help to reduce or limit the demand?

Future demands for water by the different users may be affected by technological developments. Technological developments that will increase the demand for water are for instance:

- Water cooled nuclear power generation
- Gas production from coal
- Electrification of railways etc.

Technological developments that will decrease future demands for fresh water are for instance:

- Gas cooled nuclear power generation
- Power generation by nuclear fusion
- Wind and hydropower generation
- Recirculation of cooling water
- Improved cooling tower technology
- Air cooling
- No-rinse washing technology
- Bioprocessing to provide food
- Genetic development of drought resistant plants
- Subirrigation and drip irrigation
- Desalinization of sea water

Of some technological developments it is not clear whether they will increase or reduce water demands; for example:

- Solar energy generation
- Geothermal energy generation
- Advanced communication systems
- Environmental management

Although technology may help to reduce demand, this will probably not be enough. To prevent the mining of limited resources, it will be necessary to reduce the demands of the individual users.

There are substantial differences in per capita demands between countries and between regions. Differences in demand are attributed to both natural and economic factors. More water is used in warm and dry regions than in temperate and humid areas, due to irrigation, bathing and air conditioning. Of the various climatic influences, precipitation appears to have the greatest effect on per capita demand, primarily as a result of irrigation water demands. The living standard of the population also affects the demand. Water consumption increases with an increase in living standard.

Before investigating the possibilities to influence demand (see Section 4.3), we shall analyze the demand and techniques to forecast demand.

4.2. Projections of water demand

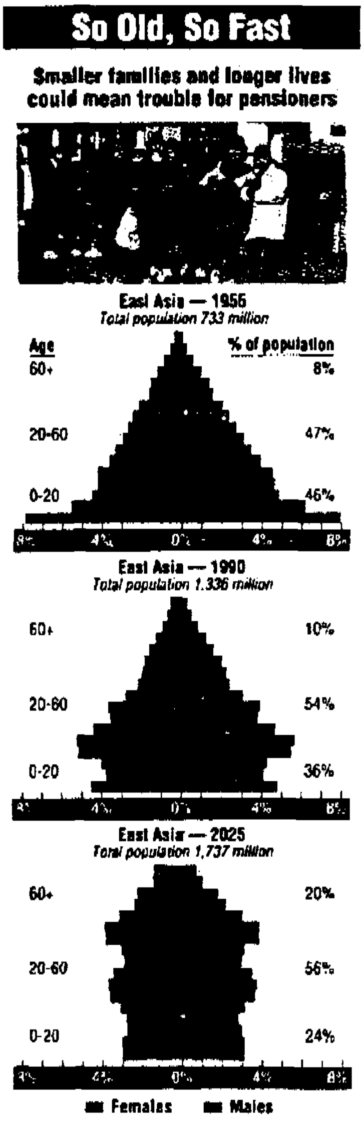
Population projections (source: Goodman, 1984)

For almost every water resource project, population projections (total and areal distribution) are needed to accomplish one or more of the following:

- Estimate demands for specific outputs of the water resource project (municipal water supply, power, etc.)
- Assess the likelihood that a project built to exploit a water resource will find an adequate market.
- Schedule the implementation, including staged development, of water resource projects.
- Provide the population component in a regional economic model. Such a model predicts, among other things, the need for various types of project outputs and the economic impacts attributable to the water resources development.

Population projections should be made for the short term (2 to 5 years) and for the medium term (5 to 10 years). Projections for the long term future (more than 10 years) are generally useless for strategic planning purposes, because of too much uncertainty, but they may serve as an indicative estimate. Such an estimate may be particularly useful when resources are limited. Forecasts made could be used to create awareness with politicians that something substantial has to be done to solve future problems. The projections, however, are too insecure to be used as a basis for planning.

Looking back, we may conclude that long term forecasts have seldom or never been even close to correct. In the United States low estimates made during the economic depression of the 1930s differed substantially from post-World War II values due to the post-war baby boom and the increase of migration to urban areas. Also, extrapolations based on post-World War II growth rates appeared to be too high due to a reduction of the birthrate. Over the last decades, all over the world, surprise changes have occurred that caused growth rates to seriously deviate from projections. Some of these unexpected changes are: the outbreak of wars, migration by refugees, political changes, the oil crisis, economic recession or economic revival, migration to urban areas, etc.



So Old, So Fast

Smaller families and longer lives could mean trouble for pensioners

On the short and medium term, an inaccurate forecast would generally mean that the schedule for implementation of a group of phased projects must be speeded up or slowed down; but sometimes serious problems may arise. For example, a project may be a financial (or economic) failure if inadequate revenues (or benefits) are realized due to overoptimistic projections.

The basic equation of balance in population studies is:

$$\frac{dP}{dt} = B-D+I-O \tag{4.1}$$

where:

$P(t)$ = population at time t in capita (cap)
B = number of births per unit of time, e.g. per year (cap/a)
D = number of deaths per unit of time in cap/a
I = immigration in cap/a
O = emigration in cap/a

It can be seen at once that Eq.(4.1) has a large similarity with the water balance, in which the population represents the storage, the births the precipitation, the deaths the evaporation, the immigration the inflow and the emigration the outflow.

The number of births can be expressed as the product of the fertility rate f and the population:

$$B = f\frac{P}{L} \tag{4.2}$$

where L is the life expectancy in years. The fertility rate is expressed in the amount of children born per person. Hence, the fertility rate equals one if each woman, on average, gives birth to two children.

Similarly, the number of deaths can be computed from the death rate d:

$$D = d\frac{P}{L} \tag{4.3}$$

In a steady state situation, $d=1$ and $D=P/L$. However, if a population is growing, meaning that there are, in relative terms, far more young people than old people, then d can be less than unity. Similarly, if $f<1$ (as is the case in China) a time will come when there are relatively far more elderly people than young people, resulting in a death rate higher than unity.

If we neglect, for the sake of the argument, the emigration and immigration, combination of Eq.'s (4.1), (4.2) and (4.3) yields:

$$\frac{dP}{dt} = (f-d)\frac{P}{L} \tag{4.4}$$

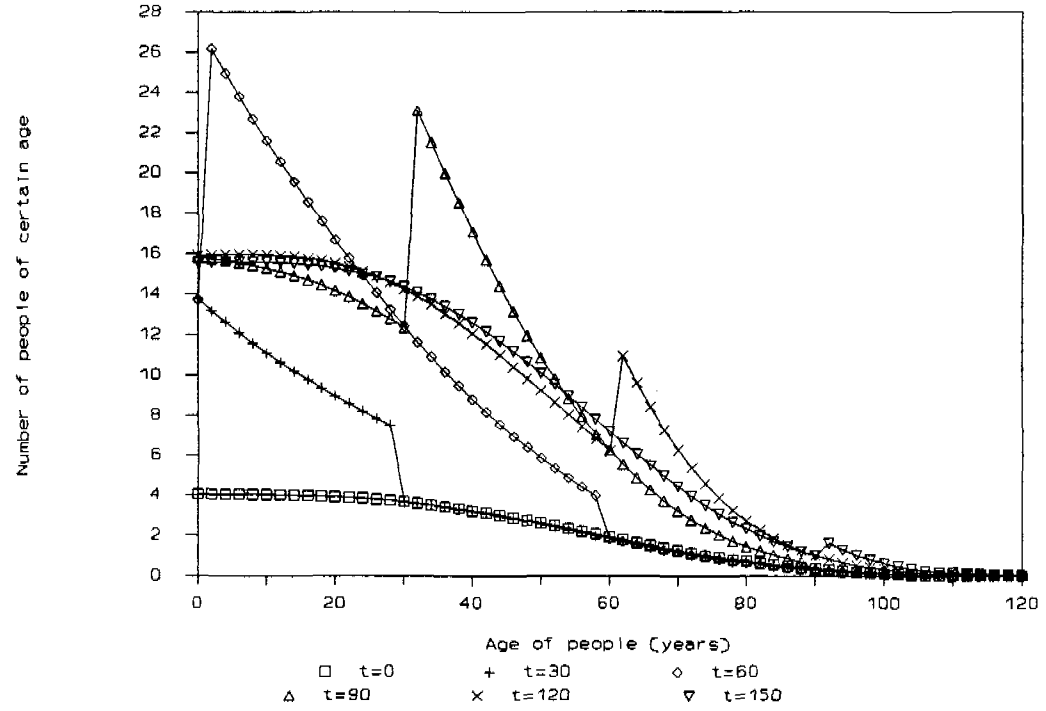


Fig.4.1 Population distribution over age classes (population pyramid) as a function of time

If f and d are constants, then the solution of Eq.(4.4) is an exponential equation of the type:

$$P(t) = P(0)\exp\left(\frac{(f-d)}{L}t\right) \tag{4.5}$$

If $(f\text{-}d) > 0$, meaning that per capita more children are born than that people die, then the population increases exponentially. If $f=d$, the population is constant. In China, where $f=0.5$, this point has not yet been reached. The adjustment to a lowering of the fertility rate takes time, because the death rate is not equally distributed over the age groups. If $f=1$, the fertility rate is equal to the replacement rate, which eventually will lead to a constant population but the time scale for reaching a death rate d equal to $f=1$ is the life expectancy L.

To illustrate this phenomenon, the following example shows what happens if in an initially stable situation, where $f=d=1$, the fertility rate is instantaneously doubled to $f=2$ at $t=0$, and where at $t=60$ years, as a result of government policy, the fertility rate is restored to the sustainable level of $f=d=1$. Figs. 4.1 and 4.2 show the population distribution over age classes and the variation of the total population P over time, respectively. The initial population distribution over age classes (also called population pyramid) at $t=0$ is stable since the same amount of people dies and is born annually. The baby boom then lasts 60 years. Subsequently, it takes another 100 years, the lifetime of a person, for the baby boom to disappear completely and for the population to stabilize.

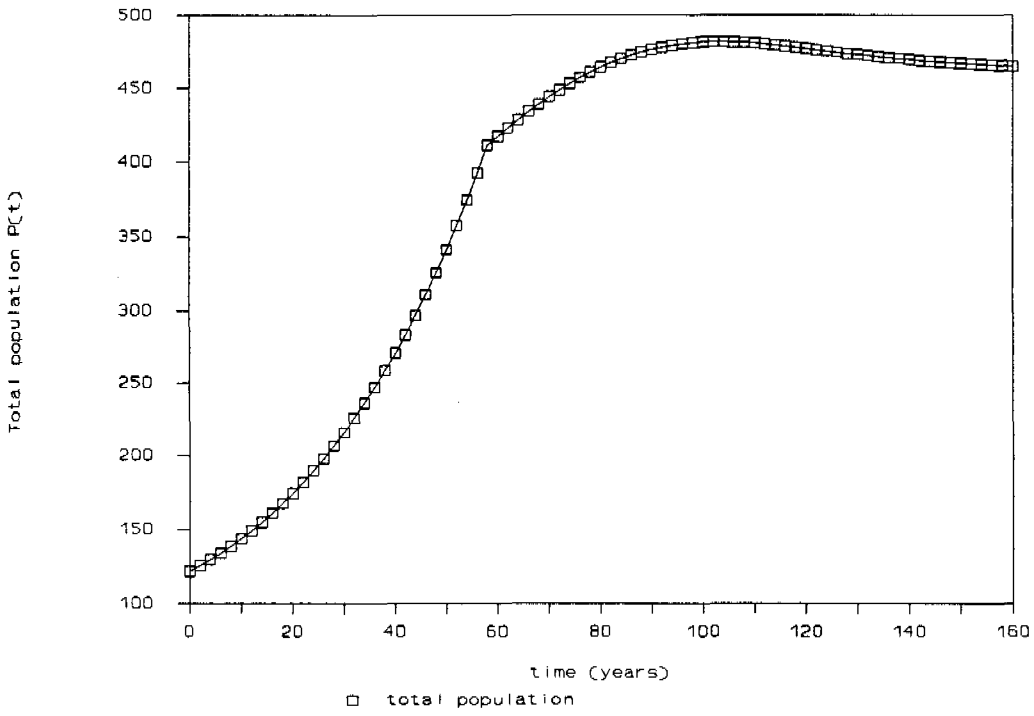


Fig.4.2 Variation of the total population *P(t)* over time

As a result of the exponential character of population growth expressed in Eq.(4.5), the outcome of population forecasts is highly sensitive to the assumed value of *f*. Therefore, estimates of *P(t)* are often based on historical records.

Population projections may be based on a time-series analysis of data for *P(t)* as a whole or for each of the components of the equation. In some cases useful correlations can be found between the population growth in the study area and another area for which more reliable projections are available (e.g. the nation as a whole).

In the following, as an example, population projections are presented which were made for Kingston and surrounding areas in Jamaica by TAMS (1977). The approach in this study was to review and compare existing projections and to develop a range of growth possibilities. The best documented projections had been made by Roberts (1976) and by the Town Planning Department (TPD, 1973).

Roberts made projections of population for the country as a whole in conjunction with internal migration among the 14 districts of Jamaica. He placed particular emphasis on movements to the Kingston's district, because he found that the city exerted a strong attractive force on all other districts. Roberts assumed three scenarios. Projection I represented the results of completely uncontrolled growth by assuming no reduction in the fertility rate from the high values observed in 1970, constant mortality, and no emigration. Projection II introduced a growth constraint in the form of declining fertility levels by assuming that fertility would fall to replacement level by 1985 and thereafter remain constant. Projection III added a second constraint on growth in the form of emigration corresponding to the fairly high levels of the 1960s. The Town Planning Department also

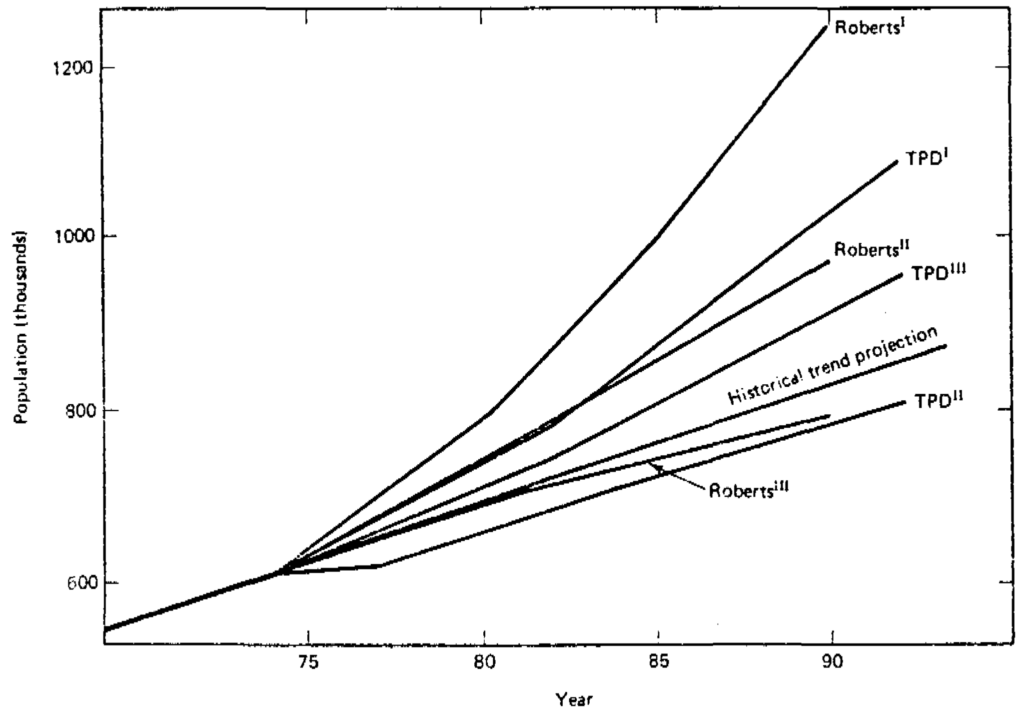


Fig. 4.3 Population projections for Kingston, Jamaica (from TAMS, 1977; source: Goodman, 1984)

made three projections. Projection I, the highest by the agency, was based on a constant growth rate and stable fertility rates. Projection II was the lowest and took account of declining fertility. Projection III was a midrange estimate. The various projections by Roberts and TPD are presented in Fig. 4.3. This figure also shows a historical trend projection, obtained by graphical extension of the historical growth experienced in the period 1960-1974.

An analysis was made to determine whether the densities of population implied by the projections were reasonable. The high rate of growth implied by Roberts I projection (a doubling of the population in 16 years) did not appear possible due to a lack of available open land space. If Kingston were to reach the densities envisaged in the Roberts I and TPD I projections, there would have to be radical changes in building patterns as well as significant investments in public high-density housing. The assumptions in the Roberts I and TPD I projections of constant fertility rate and no emigration were also judged unrealistic. For these reasons, these projections were not considered to be within the range of feasible growth patterns.

For the purpose of studying various water supply options, it was decided to adopt Roberts II projection as the high projection and the TPD II as the low projection. The historical trend projection was taken as the "most likely" projection.

This example is not a recipe for demographic projections. Each country and each region has characteristics that make it virtually impossible to prescribe one overall methodology. However, the example makes clear that one has to study well all the typical characteristics of the area and to think well about how realistic certain extrapolations are with respect to the carrying capacity of the land and the physical infrastructure.

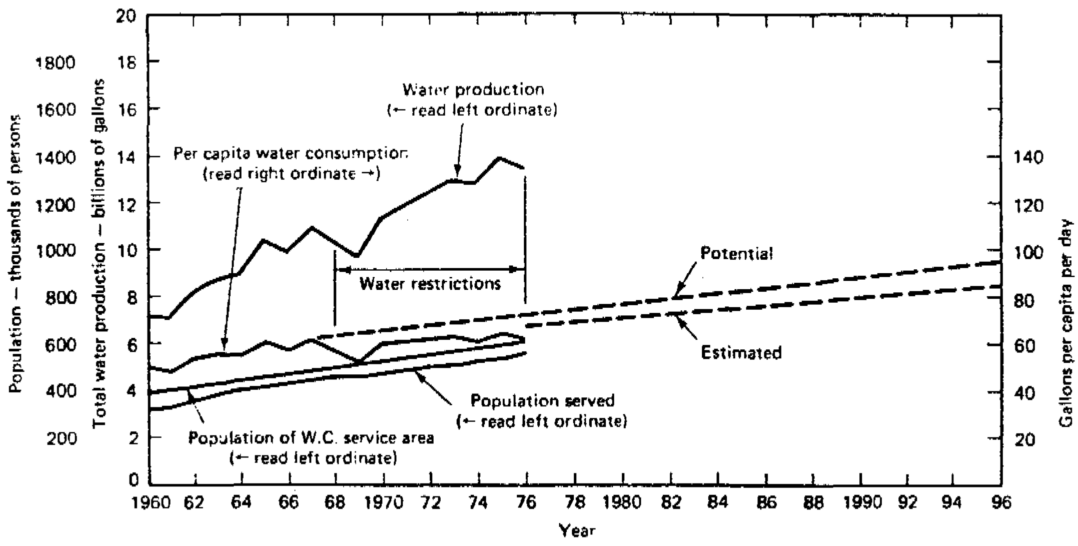


Fig. 4.4 Historical and projected water consumption for Water Commission (W.C.) service area, Jamaica. (from TAMS, 1977; source: Goodman, 1984)

Public water supply projection (source: Goodman, 1984).

Projections of public water demand should be based on an analysis of historical demand. In the following, we continue with the study of the water supply needs of Kingston by TAMS (1977), as an example. In this study, it was found convenient to calculate per capita water demand, and consumption, as the total production divided by the total population, irrespective of the specific use. Such a value differs from those based on water sales.

Fig. 4.4 shows the trends of water production, population, and per capita consumption in the service area between 1960 and 1976. The figure shows that per capita consumption did not rise in the later years. This was largely due to the unavailability of water rather than to static demand. Summer water restrictions were in existence since 1968. In 1975, there were restrictions during 194 days of the year. It was thus reasonable to assume that potential demand was significantly higher than actual demand.

Two projections of per capita demand were made. The first, which gave a potential per capita demand of 100 imperial gallons per day (0.45 m^3/d) by the year 2000, was based on extending the historical trend prior to the imposition of restrictions. It was believed more reasonable to adopt another estimate which implicitly accounts for such factors as changing demand patterns already brought about by continued summer restrictions which resulted in the adoption of measures to conserve water, and some degree of price sensitivity. This gave an estimate of per capita demand of 90 imperial gallons (0.41 m^3/d) by the year 2000, which was applied equally to all consumers in the region. These per capita demands include industrial requirements but not irrigation demand. It was assumed that existing irrigation projects would continue to be served by their sources of supply, and that new projects would be served by other supplies.

The projected water demand by 2000 for the total region, assuming "most likely" population growth (see above) would be 0.53 Mm^3/d. For purposes of sensitivity analysis, demand projections for the entire region were made for the assumed high and low growth rates as well. The implications of these different possibilities lie in the timing of any future water supply scheme for the incremental capacity needed, and in the financial returns of the project.

The forecasts discussed are based on single projections of overall per capita demand. This approach is reasonable when industrial and irrigation requirements are not too important components of the total demand. When these are important components, it is advisable to formulate a predictive model incorporating projections for the separate components of demand, using sample data for selected activities and estimates of typical requirements.

Irrigation and hydropower projections

The projections of water demands for irrigation, hydropower and other projects very much depend on national planning priorities. The need for these projects should be determined as a function of national objectives and constraints and translated into water demands on a project by project basis.

As part of the policy analysis to be carried out by the national planning authorities priorities have to be set in view of the limited resources available (water resources, financial resources, land resources, mineral resources, human resources, etc.). The determination of the water demands of each project is a straightforward exercises to be carried out by the relevant professionals: agricultural engineers, hydro-power engineers, etc.. The lecture Water Using Activities will deal with these water demands in more detail.

A lot of benefits can be gained from improving the efficiency of water use for irrigation. Irrigated agriculture uses 80% of the available fresh water, and the efficiency of this water use is very low (about 50%). This means that large quantities of water are wasted. Considerable economies can be realized if agricultural water is used in a more efficient way.

Although, from a water resources point of view, one could argue that losses in agricultural use are not always losses to the water resources system, because large parts of the wasted water re-enters the system through return flows and groundwater replenishment, a low efficiency of water use is [illegible] in a number of ways:

- high gross water uses at a certain intake implies that upstream from the intake, and directly downstream, less water can be used; a higher efficiency implies that more water can be allocated upstream;
- the design of the irrigation system is more expensive because the canals and inlet works have to be designed at too high a capacity;
- low efficiencies are related with poor and centralized water management; striving for a higher efficiency will improve the management in general;
- return flows always have a poor quality; the cost of treatment of return flows is proportional to the volume of polluted water; a low efficiency results in higher return flows, and hence, higher treatment costs.

The FAO and IPTRID, the International Program for Technology Research in Irrigation and Drainage of the World bank realize that enhancing water use efficiency in irrigation is one of the most important things to achieve in the coming years. Research in improved irrigation technologies is one aspect of enhancing efficiency, but even more important is demand management.

4.3. Demand Management

At the Dublin Conference on Water and the Environment in 1992, one of the leading principles adopted by the 114 countries, 14 UN organizations and 38 NGO's present was that water has an economic value in all its competing uses and should be recognised as an economic good.

Supply versus demand

Although the concept of water as an economic good has long been promoted, it is - in practice - still far from universally shared. In many countries, water is still considered a free good, which should be provided at low costs in the amounts and qualities desired. Moreover, water authorities tend to be supply oriented, without considering the actual need for water by the users. A supply oriented approach supplies water in such quantities as estimated necessary by the water manager and assumes that the user will make proper use of it. Experiences in supply oriented irrigation systems have shown that such systems waste considerable amounts of water, and similar experience have been gained about the efficiency of public water supply systems.

A demand oriented approach, on the other hand, looks at the real demand for water, which can be measured through the willingness of the users to pay for the water. A demand oriented approach works two ways: 1) it urges the producer to efficiently produce good value for money (if he fails to do so, the users will refuse to pay), and 2) it creates awareness among the users that the resource is precious (they have to pay for it). In addition, a demand oriented approach allows the water manager to actually influence demand. In a world where water demands are ever growing, water managers can not just continue to supply water without trying to actually influence demand. Besides managing the supply, e.g. through the building of reservoirs (supply management), they should also endeavour to manage the demand.

The activities involved in influencing demand are generally referred to under the title of demand management. Demand management, as is stated in UNDTCD's (1991) contribution to the Dublin Conference on "Legislative and Economic Approaches to Water Demand management", is probably the most important instrument that water resources managers have to develop and use during the coming decade.

Demand management is defined as:

> The development and implementation of strategies to influence demand for the efficient and sustainable use of a scarse resource.

The reasons why water managers and decision makers at all levels (national, provincial, local) should try to control demands for water are:

- the use of water is ever increasing, whereas resources are limited;
- water resources are deteriorating rapidly, either through over-utilization or pollution;
- the costs of developing new resources are increasing, since the cheapest sources of water have already been developed;
- financial constraints limit investments;
- shortages are already occurring worldwide and;
- the environmental carrying capacity of water resources systems is limited.

The aim of demand management is:

- to safeguard the rights of access to water for future generations,
- to limit water demands,
- to ensure equitable distribution,
- to protect the environment,
- to maximize the socio-economic output of a unit volume of water, and hence
- to increase the efficiency of water use.

The character of Demand Management is multi-disciplinary. One can not address demand management purely from a technical angle. Of course it is possible to introduce water saving by technical measures, such as: drip irrigation, leakage control, canal lining etc. But such technical measures always have financial and administrative implications which bring us to economic, institutional, legal and eventually political aspects. Hence, Demand Management includes an array of instruments:

- technical (water conservation, water saving technology, leakage control, cropping),
- economic (subsidies, tax and price policy, water tariffing),
- administrative (licenses, regulations, policing, capacity building),
- legal (water law, water rights, fines),
- educational (awareness raising, communication, education)
- operational (operating rules, water allocations), and
- political (priorities, objectives).

The combination of these instruments, will be different for each individual country depending on the physical characteristics, administrative system, and cultural environment.

In managing the demand, decisions should be taken on where, in which sector, and how water demands can be reduced. Implicitly, there will be conflicts between competing users and trade-offs will have to be made between the benefits obtained by allocating the water to different users in the context of the national economy. In this respect the main conflicts are expected to arise between, on the one hand, agricultural use and, on the other hand, industrial and urban use. Already in many parts of the world these conflicts occur and seldom are they solved in a planned fashion. In this respect it is important to note that the market mechanism is the main motivation for the farmers to take action and that it is also considered as one of the most important instruments to enhance the water efficiency in urban and industrial water use. Hence economic and macro-economic aspects play a very important role in demand management.

Demand management should be considered as one of the most important components of IWRM strategies (next to institutional arrangements and physical measures). It entails a set of actions to be taken by the water manager to reduce demand, which include:

- awareness and promotion
- education and training
- the formulation and application of implementation incentives to influence the demand for water.

Awareness raising and promotion are important activities that should be directed to both the water users and to the politicians. Water users should understand the importance of water conservation and should know in which way they can contribute to water conservation. They should be made aware that water is no free resource any more. It is the task of water managers, scientific institutes and universities to raise awareness with politicians of the impacts that shortage of water can have on the general economy of the country and on the well being of the people at large. But even more importantly, they should be aware of the potential source of international conflicts that water resources entail. Large (potential) international conflicts exist in the river basins of the Rio Grande between the USA and Mexico, in the Incomati and Limpopo catchments in Southern Africa, in the Euphrates catchment between Turkey, Syria and Iraq, in the Jordan catchment between Syria, Palestine, Jordan and Israel, in the Mekong catchment between Laos, Thailand, Cambodia and Vietnam. If we look back into history and study the sources of large international conflicts, we see that water has often played an important role, even at a time that resources were not as scarce as they are today.

Education is equally important to prepare the next generation of professionals for the immense problems that they will be facing. Given the present shortage of water, the enormous expected growth of the world population over the coming years and the ever increasing environmental problems, today's professionals will have to prepare the next generation to deal with problems that go far beyond their own experience, and maybe even their imagination. Education and training will be mainly the task of universities and institutes, but the water managers should also be involved to supply the necessary practical input and to enhance on the job training.

Peter Rogers (ISPAN, 1994) stated that demand management consists of four P's:

- preachments, being awareness raising, moral persuasion and threats;
- prices;
- politics, being concerns for equity;
- practices, being technical control mechanisms for water supply and conservation.

I would like to add a fifth P to that:

- policing, without which demand oriented measures can not be implemented.

Implementation incentives

Implementation mechanisms are the **tools** with which we implement demand management. These are part of institutional arrangements. An important component of these implementation mechanisms are implementation incentives. Implementation incentives for demand management can be grouped in two main categories (Koudstaal et al., 1992):

- **Economic instruments**, which include: charges, subsidies, taxes, and regulations which create markets where water rights and emission rights can be traded
- **Legal instruments**, including for example general quota or individual licences for extraction or discharges and ambient water quality standards. Such regulations are often combined with financial enforcement incentives such as fines and penalties.

Table 4.1 presents a more detailed description of implementation incentives for demand management.

Traditionally, for demand management, government agencies have merely used legal instruments, applying a command and control approach: direct regulations coupled with systems of monitoring and sanctioning of non-compliance. However, the general principles of economic instruments and their importance for integrated management have been widely studied and accepted as potentially powerful tools. Discussions started about 25 years ago, but there seems to be a general reluctance (political will) to really apply such instruments. It seems that the fear for **administrative burden** is one of the major reasons.

Some general principles can be derived from experiences obtained:

- Charges, fines, or taxes should be quantity-related so that they stimulated efficient use of water and promote environmentally sound behaviour. Flat rate tariffs or charges related to irrigation area or property value are far less effective. **Metering, however, is essential**.
- Until now the application of charges and **economic incentives** have seldom been used from a viewpoint of economic efficiency; they serve a financial purpose but are insufficiently used as instruments to manage water demand or to reduce emissions.
- The legal environment has major impacts on the possibilities for an efficient allocation.

IMPLEMENTATION INCENTIVES FOR DEMAND MANAGEMENT

CHARGES may be considered as a price to pay for the utilization of water resources (intake and discharge of residuals). The incentive effects depend on the total costs in relation to the production costs of the activity involved. Charges are used for both financing and regulation.

- user charges are paid for utilization of water or the use of public facilities such as treatment plants, based on volumes or hectares of land.
- effluent charges are paid on discharges into the environment.
- product charges and tax differentiation are applied on final products or some product characteristics (sulphur content in mineral oil, sugar in alcohol).
- administrative charges such as control and licensing fees as payment for government services.

SUBSIDIES refer to financial assistance, such as:

- grants or soft loans can be supplied to water users that wish to invest in water saving measures, or measures that improve the water quality.
- tax allowances and tax exemptions can be given to manufacturers that use environmentally sound technology. Examples are accelerated depreciation or tax exemptions if certain measures are taken. Tax related measures have direct impact on profits.

MARKET CREATION refers to the creation of an artificial market where water rights, emission rights, products and residuals can be traded.

- tradeable water or emission rights as an alternative to user charges or effluent charges.
- market intervention, for example subsidies in case market prices fall below a certain minimum. In case of agriculture, these interventions can have considerable impact on water consumption.
- liability insurance establishes: 1) liabilities for environmental damage; and 2) a market in which risks of damage penalties are transferred to insurance companies, which would calculate lower premiums when industrial processes are more secure.

FINES or financial enforcement incentives are closely related to legal instruments, but with financial implications for compliance or non-compliance.

- non-compliance fees are imposed after non-compliance, for example, related to profits made during non-compliance.
- performance bonds for example refer to a refund after compliance.

Table 4.1 Implementation incentives for demand management (Source: Koudstaal et al., 1992)

Although there still is a strong reluctance with governments to initiate demand management, still the understanding is growing that the application of demand oriented measures is crucial in future water resources management (OECD, 1989). The main prospects and corresponding bottlenecks are:

- Application of user and emission charges seems still one of the most promising measures. In developing countries, application of such charges, which are virtually non-existing, are expected to have both an important financing and regulating effect.
- In both developed and developing countries, application of economic instruments may have considerable administrative implications: monitoring of performance; new legislation and regulation; and new agencies or new tasks for existing agencies.
- Another type of administrative implication may stem from the fact that shifting from a command and control approach towards economic incentives implies deregulation and a reduced direct government involvement. This may be an official government policy, but it is likely to encounter political and administrative problems.
- Application of economic instruments can only be effective if there is a political will for policy integration, encompassing all economic sectors involved. For example, charges applied by the water resources manager can only be effective if they are not counteracted by compensating measures from the sectoral agencies involved.

Water Pricing

One of the most topical tools in demand management is water pricing. At the Dublin and Rio conferences, as reported in Agenda 21, it has been recognized that water should be managed as an economic good, provided water for drinking purposes and other basic needs are made available at prices that are widely affordable locally. Providing water free of charge, or heavily subsidized, in the past has led to serious mis-allocations of water resources, inefficient use and overexploitation.

A good illustration of this problem is the "free water dilemma". If water is for free, water industries do not receive sufficient payment for their services. Consequently, they are not able to maintain their systems adequately and, hence, to maintain the quality of their services. Consequently the system collapses, people have to drink unsafe water or pay excessive amounts of money to water vendors, while wealthy people receive piped water directly into their houses, for free. So the water-for-free policy results in rich people getting water for free and poor people buying water at excessive rates or drinking unsafe water.

Water pricing has a number of important consequences, which makes it a key instrument for the implementation of demand management:

- increased price reduces demand;
- increased price increases supply (firstly, because marginal projects may become affordable; and secondly, because it becomes attractive to reduce losses);

- increased prices facilitate reallocation among sectors;
- increased prices improve managerial efficiency.

Water pricing has now been taken up by a number of ESAs, particularly The World Bank (1993), as the most important tool for demand management. Indeed, water pricing is an important element of demand management, but it is not the only issue that requires attention. Other facets of demand management, dealing e.g. with various aspects of improved efficiency, merit attention as well.

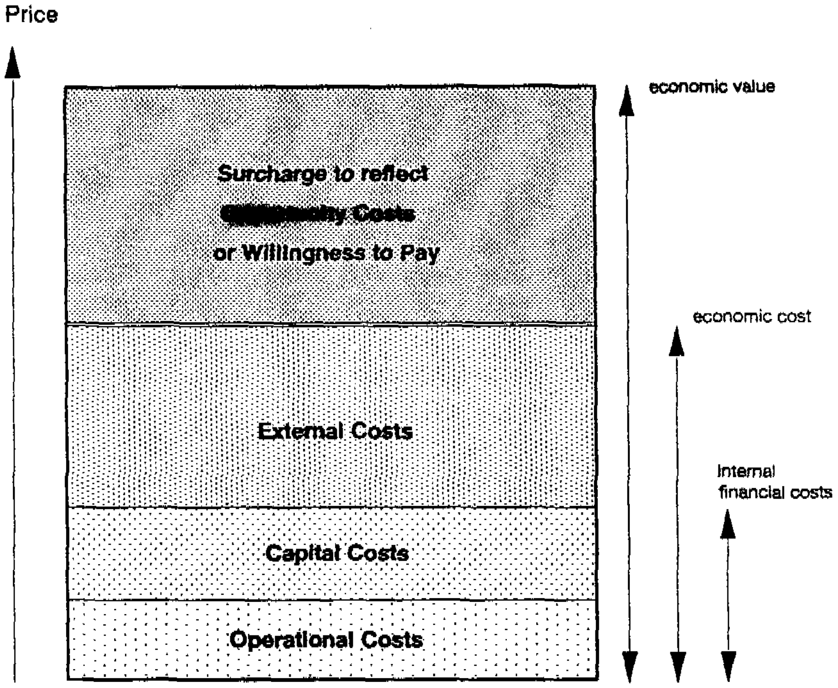


Fig. 4.5 Composition of Water Price

The water price is composed of many different elements that reflect production **(financial)** costs, **economic** costs, the economic value of the commodity, and the client's **willingness to pay** (see Fig. 4.5). Water pricing should have **two purposes: the first purpose is to recover costs, the second is to enhance water use efficiency**. In **cost recovery**, a distinction should be made between **internal financial costs** and **external (or social) costs**. From a financial point of view, the water should be priced to cover the operational costs (see Fig. 4.5), made to supply the water related goods and services, and to cover the depreciation of the infrastructure (capital costs). Economic costs include, in addition to the financial costs, also external costs, such as environmental damage and societal costs (health hazards, resettlement, etc.). Until this point the price reflects the total costs incurred by society in the production of the commodity. In addition, the economic price should reflect the scarcity of the resource, which is generally expressed in the **opportunity cost** (the cost of not being able to use the resource for another economic activity). This opportunity cost depends on the willingness to pay by users, which is reflected in **price elasticity** curves (see Section 4.4). The economic value and the willingness to pay is not easily determined. Some users are willing to pay a higher price than others. Since these are often financial rather than economic (societal) considerations, willingness to pay is not always the right argument to establish the economic price (to prevent that water always goes to the highest bidder. In addition, willingness to pay is dynamic, depending on many parameters which include affordability, scarcity of the resource, and appreciation for the resource. Since all these parameters are time dependent and can be influenced by external and internal factors, the [illegible] to pay is a volatile parameter.

Although Fig. 4.5 is useful as an illustration of how the price of water should be established to reflect societal costs, recently, water economists at the World Bank have come to the conclusion that the water price should not be based on opportunity costs or long-term marginal costs, but that it should be a [illegible] price between zero and the cost of desalination (about 2 US$/m^3) which should at least reflect the financial price, and which should send out the message to users that we are dealing with a precious and finite resource.

OECD recommendations

According to the OECD (1989), the water user should be required to pay the full social cost of providing water and related services, including treatment and damage costs. In this respect all users should be charged: consumptive users, dischargers (polluters), and non-consumptive users.

In most OECD countries, industrial and agricultural sectors are by far the largest water users. They are, however, charged only the operation and maintenance costs and not the capital costs and external costs (see Fig. 4.5). These [illegible] are therefore heavily subsidised and the economic and environmental costs of such subsidised use of water services are substantial and widespread.

Both surface water and groundwater are used as recipients for waste water discharges. The concept that polluters should also have to pay for the cost of water treatment is now widely accepted in the case of public sewage treatment, but has not been adopted in other situations.

There are market incentives and sanctions to modify resource use. The correct price for natural resources should properly reflect their marginal social rather than operational cost. The resource pricing principle proposes that the price charged for water services should be the full social cost of using resources including capital, operation, maintenance and environmental (= external) costs associated with its use. In this respect the following questions need to be answered in the near future:

- How should we determine the full social cost with respect to long-term marginal social costs and external environmental costs?
- How should we identify users (consumptive users, non-consumptive users and polluters) to which costs should be charged?

4.4. Relations between price and demand

According to Goodman (1984) the economic value of a product or service from a water resource project is correctly estimated as the amount users are willing to pay for it (although we have seen in the previous Section that it is not that simple). Goodman argues that in this respect it does not differ from any other commodity (which is not entirely true since water is essential to life and there is no alternative for it, whereas the same can not be said for most other commodities). But let's assume he is sufficiently right for our purpose.

The variation of the willingness to pay can be shown conceptually by a curve of price per unit of demand *P* versus quantity of demand *Q*; see Fig. 4.6. The demand curve is constructed in principle on the assumption of constant prices for other goods, constant incomes, and constant preferences. When any of these change, the demand for system outputs may shift.

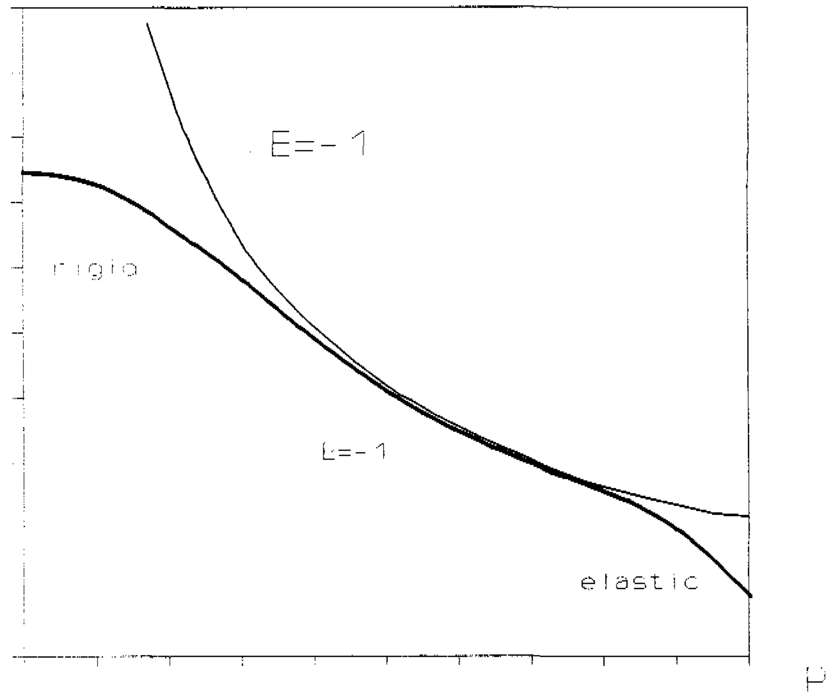


Fig. 4.6 Typical relation between Price and Demand for private water consumption

The price elasticity *E* of demand is defined as:

$$E = \frac{\mathrm{d}Q/Q}{\mathrm{d}P/P} = \frac{P\mathrm{d}Q}{Q\mathrm{d}P} \tag{4.6}$$

Hence the elasticity is the dimensionless slope of the curve in Fig. 4.6. If $E<-1$, the response to a price increase is said to be **elastic**, or reactive; if $-1<E<0$, the response is said to be inelastic, or **rigid**. The symbol on the curve marks the point where $E=-1$. To the left of this mark, the relation is rigid; to the right it is elastic. If, for example, the price is increased by 100%, and this results in a 20% decrease in demand, the elasticity is -0.2, which is rigid. The rigidity can be higher for necessities (such as water), than for luxuries. Since water is no luxury, water demands reduce relatively little with an increase in price.

One can argue that with respect to drinking water the demand-price relation is never going to be more elastic than -1. If someone has 100 $ to spend on water (*QP*=100), then for *QP* to remain constant, a price increase of 10% should be compensated by a consumption reduction of 10% (*E*=-1). This is assuming there is no cheaper alternative for water (e.g. buying it from water vendors). However, there is no need to save more water than 10%, since that would imply spending less than 100 $ on water. Hence price-demand relations for drinking water are always inelastic ($-1<E<0$). Only when people are no longer able to receive sufficient water for the amount of money that they can make available for the purpose, they will look for other options (digging their own wells, using untreated water) or move out of the area. Only then shall the relation become elastic ($E<-1$), as indicated in Fig. 4.6, but such is hardly the situation which a water manager would like to reach.

Price-demand relations that are based on a fixed amount of money that people can spend on water are all of the type:

$$Q = \frac{c}{P} \qquad (4.7)$$

where *c* is the amount of money people are willing, or able, to spend on water. These functions have a constant elasticity of -1 (see Fig. 4.7).

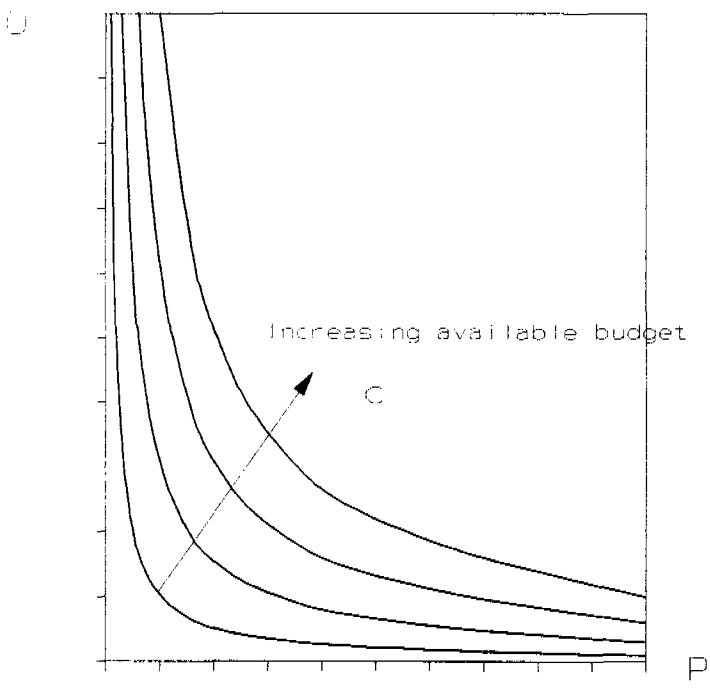


Fig. 4.7 Relations between Price and Demand for fixed water budgets (*E*=-1)

There is a fast literature on the price elasticity of water demands in residential, industrial and agricultural uses, mainly in the USA. The consensus conclusion, according to Howe (1993), is that residential and industrial demands (except for cooling water) are inelastic while agricultural demands are more elastic. This has to do with the availability of alternative options for water use. For domestic use there is no alternative for water, and people are willing to pay a lot more for the same quantity (rigid). People must have minimum amounts of water in some form to survive, and there is compelling evidence from developing countries all over the world that households often pay extraordinary high prices to water vendors for small amounts of water. In industry and agriculture the elasticity, although still low, is somewhat higher. In arid areas there is no substitute for irrigation or industrial water (leading to low elasticity), but farmers and industrialists can invest in water saving technology and farmers can change cropping patterns (leading to a higher elasticity).

Hence, the elasticity, of water consumption is generally low. In water resources terms, domestic water supply is generally underpriced with respect to its real value and demand. Therefore this product is relatively inelastic (rigid) within typical ranges of price. It can be seen in Fig.4.6 that the demand becomes only more elastic (the curve gets steeper) when the price of the water becomes so high that people can no longer afford treated water and start looking for other sources.

The demand by certain large industrial water consumers can become elastic when prices, while still modest for domestic water supply, are increased to the point where conservation measures and alternatives (e.g. air cooling) become economic. Only then will the price become a demand management tool. Hence, demand management requires a certain elasticity of the price-demand relationship.

4.5. Experiences with water pricing and demand management

Some success has been achieved recently in the Netherlands with solid waste collection. Citizens in Haarlem are charged per container for solid waste disposal. Standard containers have a sticker with a bar-code which is automatically read by the truck as the container is lifted, weighed and emptied. Citizens are charged per unit weight. Although some administrators feared that people would dump their waste in other places, these things did not happen at any noticeable scale. Since people were well informed about the fairness and necessity of the system, they were willing to accept the measure. As a result the amount of solid waste decreased considerably because people no longer accepted unnecessary wrapping in shops and rather used returnable containers with deposit than disposable containers.

Pricing measures have also been quite successful in industry. Since producers keep close watch over their costs and benefits, an increase in the costs of water, provided the elasticity of the price-demand relation is sufficiently elastic, immediately shifts the balance to more water efficient technology. Increase in water price or in pollution charges appears to be effective with institutions that closely monitor their production costs. Industries even are willing to invest in water saving or pollution reduction technology in anticipation of price increases (Healy-Sing, 1994)

In some countries, particularly countries which suffer from severe water scarcity, water pricing has become a very normal way to regulate demand. For instance in Palestine, on the West Bank, progressive rates for water tariffs (increasing block rates) are being used. For domestic use, in 1994, the first 10 m^3 used per month is charged with 0.9 US\$/m^3. The following 30 m^3 costs 1.3 US\$/m^3. Consumptions above 40 m^3/months are charged with 1.5 US\$/m^3. In the Gaza strip, per 1 January 1995, the water tariffs are the

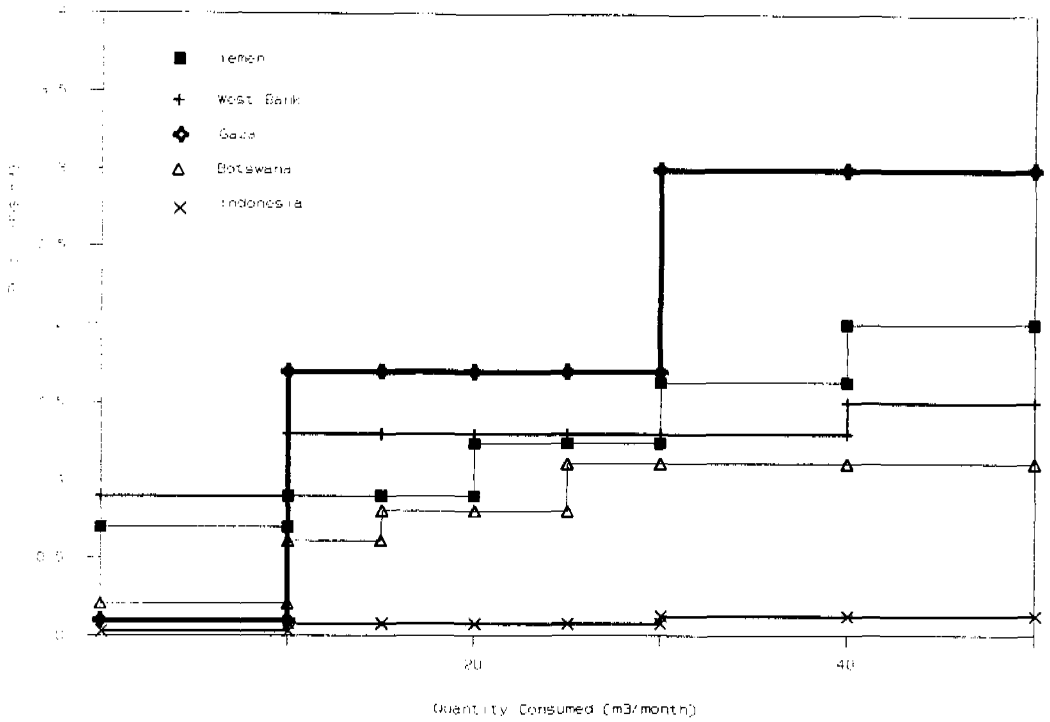


Fig. 4.8 Increasing block tariffs of drinking water for some countries

following: a base tariff of 1 US$ per connection; 0.1 US$/m^3 for the first 10 m^3; 1.7 US$/m^3 for the following 20 m^3; 3 US$/m^3 for the amount over 30 m^3. People without a meter, or with a broken meter, pay the maximum tariff of 33 US$/month. For comparison, depending on energy prices, desalination costs are about 2US$/m^3 at present (1995).

In Yemen, in 1994, the National Water and Sewerage Authority charges for water supply and waste water treatment at the same time in an increasing block tariff: the first 10 m^3 are charged with 0.70 US$/m^3 (at an official exchange rate of 12 YR/$, the unofficial rate was 100 YR/$ in 1995); the following 10 m^3 cost 0.90 US$/m^3; the following 10 m^3 cost 1.24 US$/m^3, the following 10 m^3; cost 1.63 US$/m^3, and above 40 m^3 the price is 2 US$/m^3. The increasing block rates are illustrated in Fig. 4.8.

This increasing block tariff system is a demand management tool intended to reduce excessive water consumption, while conserving the right of access to safe water for the poorer part of the people, on the basis of **economic criteria**.

The use of **financial criteria** often leads to the reverse: decreasing block rates. In some countries, a water company that uses the marginal cost criterion for determining the water price is willing to give discounts to clients that consume large quantities of water. Such is for instance the case in The Netherlands. In The Hague, the dune water company uses a base tariff of 56 US$/connection/year and a flat tariff of 1.74 US$/m^3 (1995 data). However for large consumers, who use more than 6000 m^3/year, the flat tariff is 1.68 US$/m^3. This rate is purely based on cost recovery, where a large part of the costs are incurred by water treatment, since the surface water resources of the major Dutch rivers are unfit for human consumption without extensive treatment. From a water conservation point of view, however, this practise is counterproductive and does not take into account the economic value of the water resources.

An average family in The Netherlands pays about 250 US$/year on drinking water. In addition it is charged 200 US$/year on the treatment of waste water (The Hague, 1995). The consumer receives separate bills for water and waste water. Interesting results can be obtained by combining these bills.

Combination of water and waste water tariffs

Rogers at a debate on demand versus supply management (ISPAN, 1994) reported on an interesting experiment of combining water and waste water bills. In the city of Boston, on the Atlantic Coast, the water tariffs were increased by a factor of 2.2 as a result of the building of a waste water treatment plant for the sewerage system of the city; the costs involved were recovered through the drinking water tariff. As a result, against the expectations of most (supply oriented) water managers, the demand for water reduced from 310 million gallons to 245 million gallons. Which is a reduction of 23%! Hence the elasticity of the demand was:

$$E = \frac{245-310}{(245+310)/2} \Big/ \frac{2.2-1}{(2.2+1)/2} = -0.3$$

Although according to the definition of elasticity this is still an inelastic value, the 23% reduction of water consumption is certainly not small. For the water authority such a demand reduction is substantial.

Even more impressive results were reported by the World Bank (1993). In the city of Bogor, Indonesia, the expansion of the water supply system appeared so expensive that demand management was considered. Water fees were increased by 30%, which resulted in a consumption reduction of 29%; an elasticity of near -1!. This action was followed by an awareness and education campaign aimed a the largest consumers, including advises for consumption reduction and water saving technology. This resulted in yet another 30% reduction.

5. WATER RESOURCES SYSTEM MODELS

5.1. System elements

In this chapter we deal with the infrastructural part of the Water Resources System defined in Section 1.1. The infrastructural part of the water resources system is the whole network of physical infrastructure, both natural and man-made, that is used to match resources with demands. It can be small: e.g. a village water supply system consisting of a well, a water tower, a small distribution network and stand pipes. Or it can be very extensive: e.g. a river basin authority that controls the system, maintains the system, extends the system when needed, manages supply and demand, manages the finances, sets priorities, and allocates the water.

It appears from the above, that a water resources system does not stand on its own, besides having physical characteristics, it also requires administrative and institutional qualities. These, however, are more related to management than to the physical operation of the system. In this Section, we look at the physical components of a water resources system, and how we can model the physical system.

Branches and nodes

The infrastructure of a water resources system can be represented by a simulation model which mimics the functioning of the real system. In the simulation model, the system is schematized as a network of branches and nodes, through which the water is distributed. A branch transfers water from one node into another, with or without losses; a node is a place where water can be entered into the system or diverted from the system. A node is represented mathematically by conservation of mass: $I\text{-}O = 0$ For a junction this implies that the sum of the upstream flows equals the downstream flow:

$$Q_{u1}+Q_{u2} = Q_d \tag{5.1}$$

where the subscript u refers to the upstream branches and the subscript d to the downstream branch.

In a natural system, the water flows from upstream to downstream. This may seem a trivial matter, but it is an essential aspect of a physically based water resources system model. Water can only be diverted upstream through pumping, either into a pipe line, or into a higher situated canal; just like in reality. A system model should allow these possibilities.

There are three types of branches (see Table 5.1): pipes, canals, and rivers. In a pipe it is assumed that no losses occur. The inflow equals the outflow. In a canal losses may occur through infiltration, which are defined per unit length. The total loss of a canal is the product of its length Δx in m and the loss rate q in m^2/s. In a canal the flow can in principle be both in upstream and downstream direction, depending on the operation of structures or pumps at its boundaries. A river behaves the same as a canal, with the exception that it only has unidirectional flow. In case the river or canal is fed by seepage, the loss rate is negative.

System Component	Sub-component	Mathematical Description	Regulating Mechanism	Remarks
Branch	pipe	$Q_d = Q_u$	-	
	canal	$Q_d = Q_u + \Delta x*dQ/dx$ $dQ/dx = - q$	lining to reduce loss q	q is loss per unit length Δx is the branch length
	river	$Q_d = Q_u + \Delta x*dQ/dx$ $dQ/dx = - q$ $Q > 0$	-	q may be negative (seepage)
Node	junction	$I-Q = 0$	-	
	bifurcation	$I-Q = 0$	Distribution function	Natural distribution
	structure	$I-Q = 0$	Allocation function	
Reservoir		$dS/dt = I-Q+(P-E)*A$	Operating rules $Q(t)$	
Inflow point	sub-catchment	$I(t)$	-	
	well field	$I(t)$	$I(t)$	
Offtakes	consumption point	$C = U - R$	$C(t)$ $R=R(C)$	U is use R is the return flow
	downstream requirement	$O(t)$	-	

Table 5.1 System elements and their properties

Three types of nodes are distinguished: a junction, a bifurcation and a structure. At each node, the inflow I minus the outflow O is zero. A junction is different from other nodes in that at a junction rivers (or canals) meet under gravity, without a possibility for regulation. In a bifurcation, a natural stream splits in two, without the possibility of day to day regulation. The flow is divided according to the hydraulic properties of the streams. The only way by which the distribution can be manipulated is by physical measures, such as dredging. If a structure is present in a node, then the water distribution can be managed through an allocation function.

Inflow points and water use points

Inflow points are the water sources of the system. They either are natural river sub-catchments or well fields. A well field is manageable, whereas a river sub-catchment is not.

Finally we come to the elements that represent the water use; the reason why we develop the system. Distinction is made between a consumption point and a downstream requirement. At a consumption point, the net water use, the consumption C, is withdrawn from the system; it is assumed that the return flow is directly returned to the system. Hence the consumption C equals the difference between the use U and the drainage R:

$$C(t) = U - R \tag{5.2}$$

The difference between a water use point and a downstream requirement is that the downstream requirement is not manageable or negotiable. It is a requirement which is either met or violated.

Reservoir nodes

Since branches and nodes are elements without storage, we need special elements to represent storage S. Reservoirs are special nodes where a storage function is available. The water balance equation serves as the storage function:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = I - Q + (P - E)A \quad (\mathrm{m}^3/\mathrm{s}) \tag{5.3}$$

where $A = A(H)$ is the inundated area which is a function of the topography, derived from planimetering. For flood routing purposes, a time scale for reservoir computations is used in the order of hours to days. At that time scale, local rainfall (P) and evaporation (E) can not be neglected. However for reservoir yield computations a time scale is used in the order of weeks to months. For reservoir yield computations evaporation and rainfall can not be neglected in general. In the following section a simple reservoir model is presented for flood routing and for reservoir yield analysis

5.2. Simple reservoir model

The most important equation to describe a reservoir is the water balance of Eq.(5.2). In finite differences form the water balance of a reservoir reads:

$$S_1 = S_0 + (I-Q + A(P-E)) * (t_1 - t_0) \quad (\mathrm{m}^3) \tag{5.4}$$

where P is the rainfall, E is the evaporation, A is the surface area of the reservoir, S is the storage, I is the inflow and Q is the reservoir release (outflow). In Eq.(5.4), the inflow, the rainfall and the evaporation are input data; the initial storage is an initial condition; the time is an independent variable. To determine the storage at a certain time t_1, the outflow and the surface area should be known. However, these depend on the water level in the reservoir, and thus on the storage to be computed. Eq.(5.4), therefore, can not be solved explicitly, but has to be solved iteratively.

For the solution of Eq.(5.4), three extra equations are necessary to relate the outflow, the surface area and the storage to the water level. The following type of equations are widely applicable. They may have to be modified somewhat for application in a specific case.

$$A = A(H) \tag{5.5}$$

$$S = \int_{H_0}^{H} A \, \mathrm{d}H \tag{5.6}$$

$$Q = K(H-H_c)^c \tag{5.7}$$

Eq.(5.5) is obtained from planimetering a topographical map. Often an exponential equation of the following type serves the purpose well:

$$A = A_0 \exp(b(H-H_0)) \tag{5.8}$$

where A_0 is the surface area at H_0. The equation plots a straight line on semi-logarithmic paper. But also a power function of the type:

$$A = A_0 + a(H-H_0)^b \tag{5.9}$$

can often be used. The equation plots a straight line on double logarithmic paper. Both Eq.'s (5.8) an (5.9) are easily integrated to yield Eq.(5.6).

Flood routing through a reservoir

In the case of a flood passing through the reservoir, the outflow hydrograph and the water levels in the reservoir can be computed. At the relative small time steps used for flood routing, the direct rainfall on the reservoir and the evaporation from the reservoir can be neglected.

The following procedure is commonly used in spillway design to determine the required dimensions of the spillway. Eq.(5.7) is a spillway function. In the case of a free overflow spillway, the exponent $c=1.5$ and the coefficient $K \approx 1.5*B$, where B is the spillway width; H_c is the crest level of the spillway. The equation can be modified to fit another spillway type, if required. The set of eqs.(5.4)-(5.7) can be solved iteratively:

1. Assume a certain spillway design by determining values for K, c and H_c. In most cases the simulation is started with a full reservoir:

   $$H_0 = H_c$$

2. In a first approximation, Eq.(5.4) is solved assuming that the outflow Q remains constant over the time step: $Q=Q(H_0)$ and that the effect of local rainfall and precipitation can be neglected in relation to the flood flows. The storage thus obtained is the first estimate of the storage S^*. The following equation is also called the *predictor*:

   $$S^*_1 = S_0 + \left(I-Q(H_0)\right)*(t_1-t_0) \quad (\mathrm{m}^3)$$

3. On the basis of S^*_1, H^*_1 is computed using the inverse of Eq.(5.6):

   $$H^*_1 = H(S^*_1)$$

4. With this first estimate of H_1, the estimate of S_1 can be corrected, using the *corrector*:

   $$S_1 = S_0 + (I-Q^*)*(t_1-t_0) \quad (\mathrm{m}^3)$$

   with $$Q^* = K\left(\frac{H^*_1+H_0}{2}-H_c\right)^c$$

5. The corresponding reservoir level follows from $H_1 = H(S_1)$.
6. If necessary steps 4 and 5 are repeated with H_1 instead of H^*_1 until no more significant change in S_1 occurs.
7. Subsequently, the procedure is repeated in step 2 for the following time step:

   $$S^*_2 = S_1 + \left(I-Q(H_1)\right)*(t_2-t_1) \quad (\mathrm{m}^3)$$

   until the full flood wave has been simulated.
8. At the end of the simulation the maximum reservoir level and the maximum discharge are obtained corresponding to the assumed spillway design.

The iterative procedure described, based on the set of Eqs.(5.4) through (5.7), is easy to perform in a spreadsheet. Figure 5.1 is an example of the output of the spreadsheet model RESSIMFL.

Two observations can be made from studying Fig. 5.1. Firstly, the inflow and the outflow hydrographs intersect at the point of maximum outflow; and secondly, the volume enclosed by the two curves left of the intersection is equal to the volume enclosed to the right of the intersection (assuming the water level is at the spillway crest at the start of the inflow hydrograph). The former volume is the part of the inflow which is temporarily stored in the reservoir above the crest of the spillway, the latter volume is the release of that same amount. Before the point of intersection the storage increases; after the point of intersection the storage is reduced.

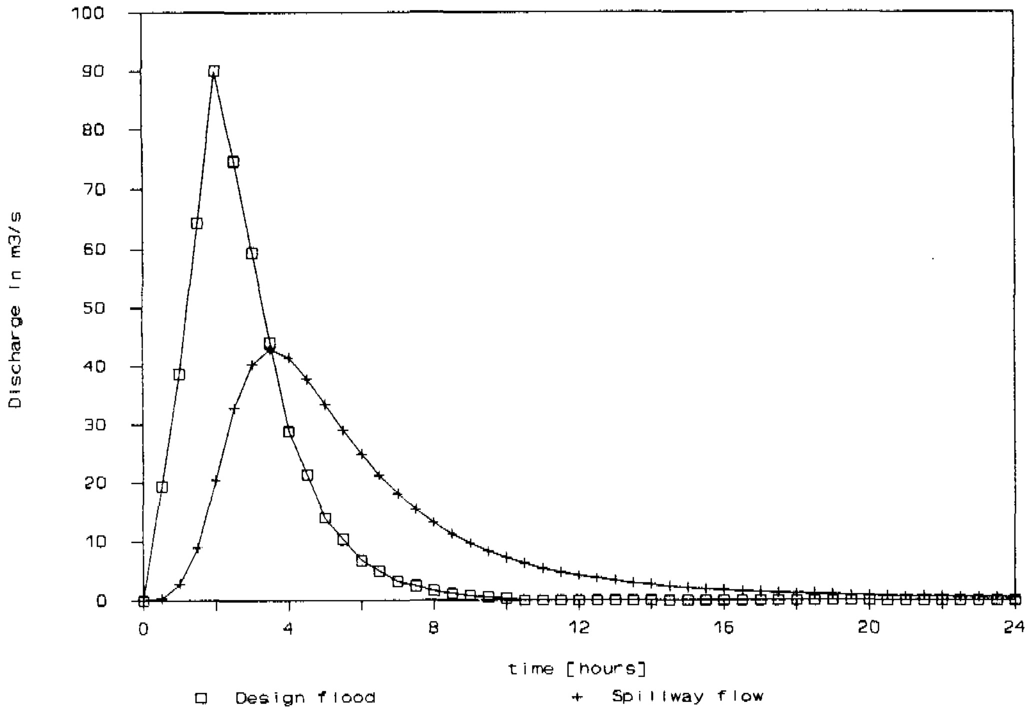


Fig. 5.1 **Inflow and outflow hydrograph of a reservoir**

That the maximum outflow occurs at the point of intersection can be made clear by the following reasoning. It follows from Eq.(5.3) that (neglecting the effect of rainfall and evaporation):

$$\frac{dS}{dt} = I - Q$$

At the point of intersection this results in:

$$\frac{dS}{dt} = 0$$

which because $S = S(H)$, and $\partial S/\partial H \neq 0$, results in:

$$\frac{dH}{dt} = 0$$

Thus the maximum water level in the reservoir occurs when inflow equals outflow. Since the outflow $Q = Q(H)$:

$$\frac{dQ}{dt} = 0$$

the maximum outflow occurs at the maximum water level.

Reservoir yield analysis

In reservoir simulation for yield analysis, the time series of P, E and I are known values. The variation of the storage S over time and the reservoir outflow, or release, Q are the unknown parameters. The reservoir release is composed of the draft, D, being the planned or envisioned release, and the spill over the spill way, L.

$$Q = D+L \tag{5.10}$$

The way the yield analysis is approached is by assuming a certain draft, possibly as a function of time, $D(t)$, on the basis of which the reservoir simulation is made. The spill, $L(t)$, follows from the reservoir operation.

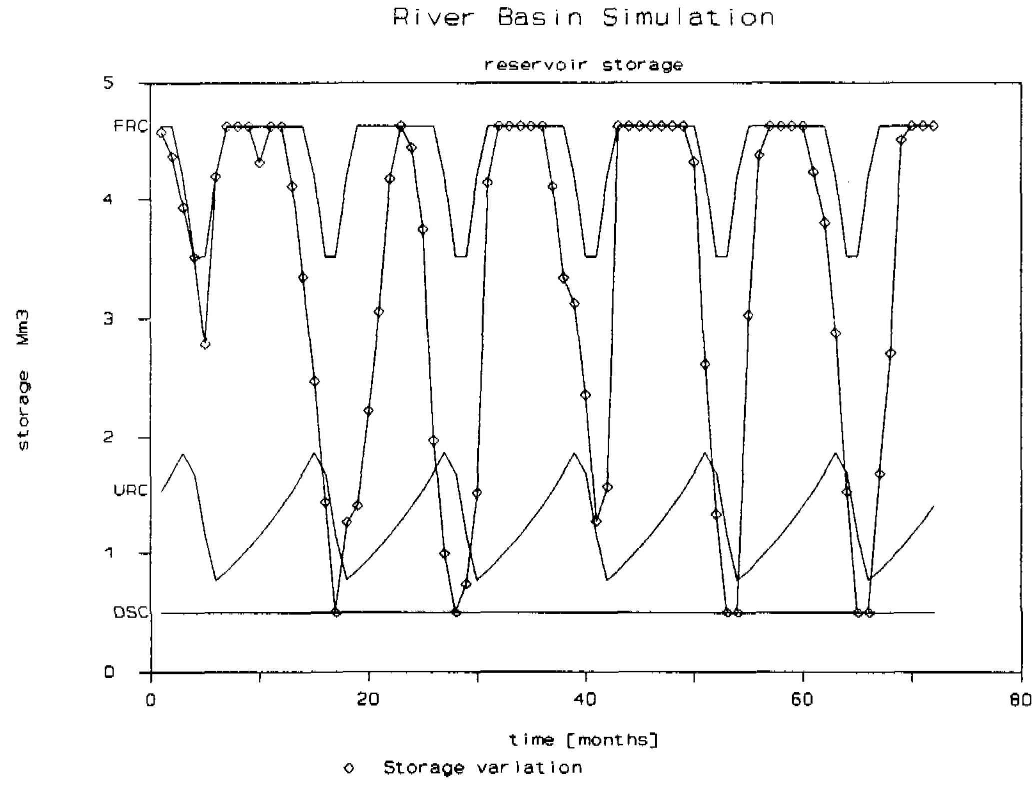


Figure 5.2 Reservoir operating rules (rule curves) and simulated storage variation by the model WAFLEX

Although, in principle, many different operating rules can be used, most reservoirs follow the basic operating rules of the following example. Figure 5.2 shows three operating rules:

- The Flood Rule Curve (FRC), which is a hard boundary (meaning it may not be crossed[1]). The FRC represents storage levels, which are a function of time, FRC(t). If the storage is more than FRC, all additional water is spilled ($L=S$-FRC):
  If $S>$FRC, then $Q=D+(S$-FRC) and $S=$FRC

- The Utility Rule Curve, URC(t), which is a soft boundary (it may be crossed). If the storage reaches, or crosses, the URC, the release from the reservoir is reduced by a certain rationing percentage r:
  If $S<$URC, then $Q=r*D$ and the water balance is redone with $Q=r*D$

- The Dead Storage Curve, DSC(t), which is a hard boundary. The storage may never drop below this level as a result of releases, only due to evaporation. The dead storage requirement is often for environmental or ecological reasons. If, as a result of the draft, the storage drops below the DSC, then the release is reduced in the following way:
  If $S<$DSC, then $Q=S+D$-DSC and $S=$DSC
  If subsequently it appears that $Q<0$ (as a result of evaporation), then S and Q are corrected: $S=$DSC$+Q$ and $Q=0$

The areas between the curves are generally called zones, and the drawing of rule curves is also called zoning of the reservoir storage. In Figure 5.2, zone 1 is the area under DSC; zone 2 is the area between DSC and URC; zone 3 is the area between URC and FRC; and zone 4 is the area above FRC. The line indicated by the symbols is the storage variation as simulated by the spreadsheet model WAFLEX.

During the simulation, the following steps are followed:

1. Establish a draft pattern $D(t)$ and assume that the release $Q=D(t)$. The inflow I is taken as the average over the time step $dt=(t_1-t_0)$.
2. Solve the water balance equation (5.2) in numerical form:

$$S_1 = S_0+(I-Q)(t_1-t_0)+(P-E)(t_1-t_0)A(H_0)$$

   where $S_1=S(t_1)$ and $A(H_0)$ is the inundated area at water level $H(t_0)$. Although it would be more correct to use the inundated area as a function of the average water level between t_1 and t_0, which would require an extra iteration in the computation, such a procedure is generally not necessary as the error made by the rainfall and evaporation term is expected to be small.
3. Check the operating rules. If necessary the release Q and the storage S_1 should be adjusted according to the operating rules.
4. Now that S_1 and Q are known, the computation for the next time step can be started similar to step 2:

$$S_2 = S_1+(I-Q)(t_2-t_1)+(P-E)(t_2-t_1)A(H_1)$$

---

[1] The FRC is only a hard boundary at the time scale used for reservoir simulation (a time step of a week, decade or month). During day-to-day operation, the FRC can be crossed temporarily during the spilling operation.

5. The above steps are repeated until the end of the data series is reached. At the end of the simulation the shortage of water is computed, as well as the amount of water spilled. On the basis of this information a decision can be taken to adjust the release pattern, *D(t)*, or to use other rule curves.

The spreadsheet model RESSIMOP is based on the Eqs.(5.4), (5.5), (5.6) and (5.10). It has the simplest set of constant (time independent) rule curves: FRC=S_{max} and DSC=0. The spreadsheet model WAFLEX uses time-variable rule curves: FRC, URC and DSC.

The inflow to the reservoir should be either a branch or an inflow point.

5.3. River Basin Simulation model

The river basin simulation model reproduces the interactions among the elements of the water resources system and describes the outcome of operating the system under a given set of inputs and operating assumptions. By successive and systematic runs of the model, the response to the variations in inputs or operating conditions are evaluated. When used in conjunction with engineering and economic criteria, the results of these runs allow: 1) the systematic comparison of alternative configurations of water resources projects in the basin; and 2) the evaluation of the effect of the upstream development on the flows at the outfall and the consequent downstream development.

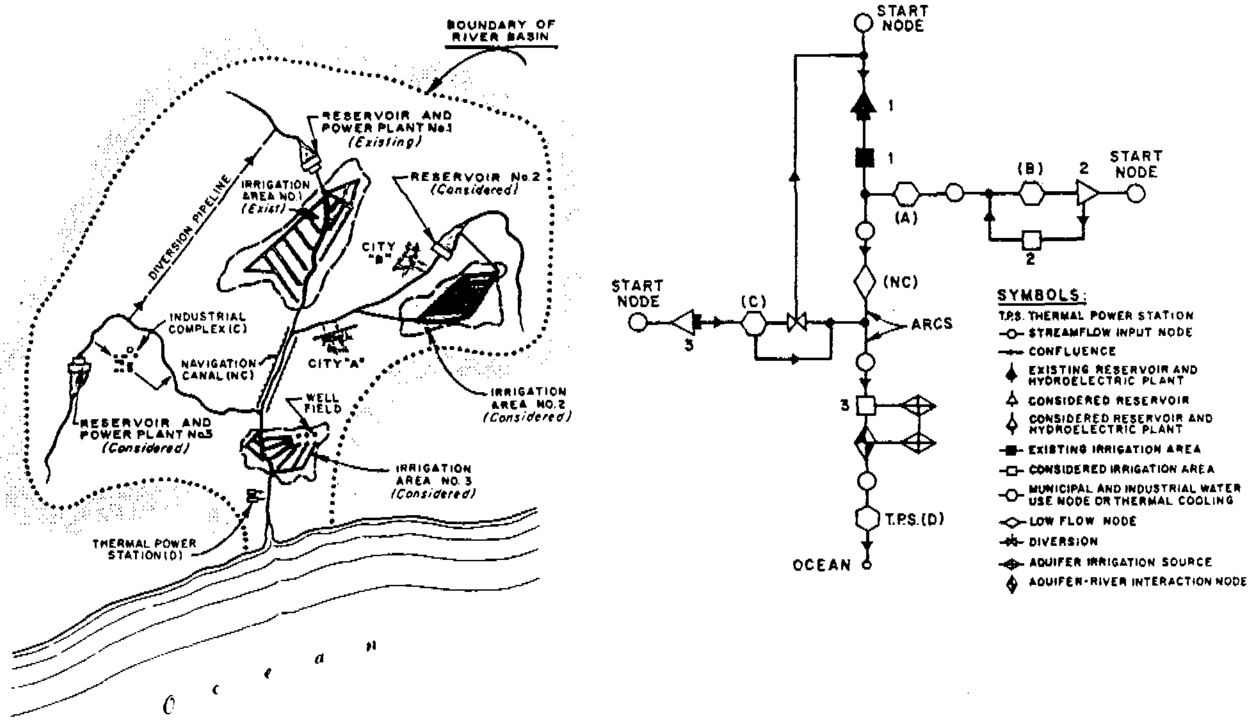


Fig. 5.3 MITTAMS, a water resources system simulation model and its schematization (source: Goodman, 1984)

As an example of such a model, the MITTAMS model of TAMS (source: Goodman, 1984) is presented in Fig. 5.3. MITTAMS is a large time-step (30 days) simulation model for evaluating the hydrological and economic consequences of various plans in a multi-unit, multipurpose basin project.

RIBASIM is a similar simulation model, developed by Delft Hydraulics, which is particularly powerful for the modelling of complex systems. Like MITTAMS it can be linked up with flow generating models, demand generating models, and performance evaluation models.

Another well known water resources system model is IRAS, developed by Loucks et al., which is an interactive system simulation model, that can be built up by the user by linking system elements in an interactive and graphical way. The model is user friendly and appealing. The disadvantage of the model is that it is supply oriented. It supplies water under pre-set conditions of demand through allocation functions. However, it does not compute the requirement for releases as a function of water demands and uncontrolled inflows from sub-catchments.

Another highly interactive and flexible simulation model, which does not have this disadvantage, but which is demand driven, is WAFLEX. It runs under LOTUS Symphony; it makes use of the spreadsheet environment for the computations and of graphical windows to communicate with the user. A model can be built by linking modular system elements together in a directly visible worksheet. The spreadsheet environment has powerful graphics that guarantees swift and efficient communication with the user. The disadvantage of WAFLEX is that it is not fool proof. It can only be operates by a professional who is conversant with spreadsheets. Figure 5.4 gives an example of the computer screen under different windows. The WAFLEX model is used in the Incomana groupwork.

5.4. Incorporation of water quality

A more comprehensive version of WAFLEX has been developed which carries out water quality computations in separate windows linked to the water quantity computations. In Table 5.2 the balance equations for a certain conservative contaminant are presented for each system element, which are the basis for the WAFLEX model.

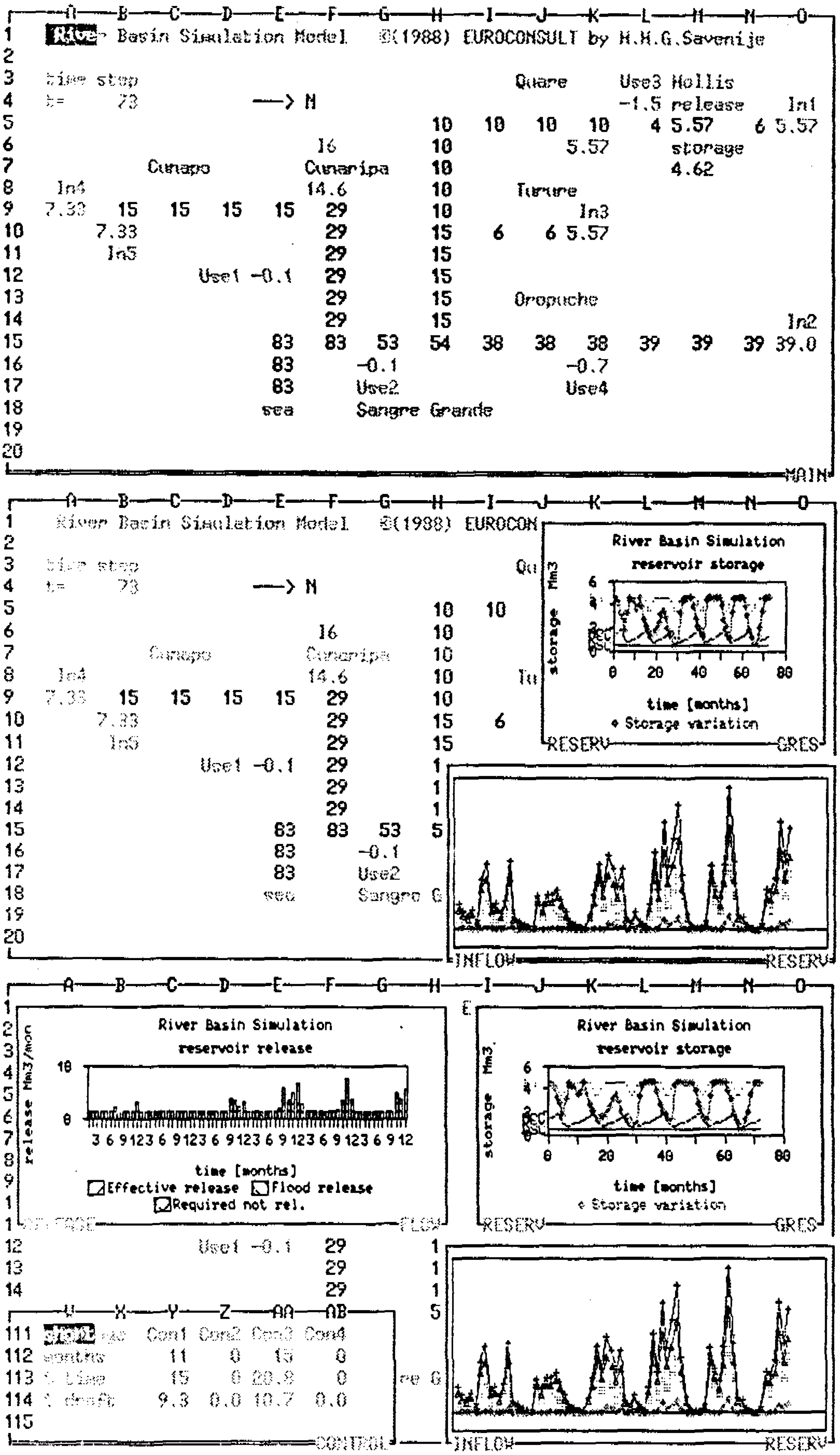
branches:

In branches with negative loss (seepage) the concentration of a dissolved conservative contaminant is changed according to the law of conservation of matter:

$$Q_d c_d = Q_u c_u + qLc_q \tag{5.11}$$

where c_d, c_u, and c_q are the downstream, upstream and seepage concentrations of contaminants respectively. In branches where the loss is positive or zero, the upstream concentration equals the downstream concentration.

nodes:



```
  A   B   C   D   E   F   G   H   I   J   K   L   M   N   O
1  River Basin Simulation Model  ©(1988) EUROCONSULT by H.H.G.Savenije
2
3  time step                                   Quare      Use3 Hollis
4  t=     73          ——> N                                -1.5 release     In1
5                                 10   10   10   10      4 5.57     6 5.57
6                       16        10         5.57          storage
7           Cunapo      Cunaripa  10                       4.62
8   In4                 14.6      10      Turure
9   7.33  15   15   15  29        10            In3
10       7.33           29        15    6     6 5.57
11       In5            29        15
12           Use1 -0.1  29        15
13                      29        15      Oropuche
14                      29        15                                   In2
15                 83   83   53   54   38   38   38   39   39   39 39.0
16                 83      -0.1               -0.7
17                 83      Use2               Use4
18                 sea     Sangre Grande
19
20
                                                                      MAIN
```

```
    W      X      Y     Z     AA     AB
111 Storage      Con1  Con2  Con3   Con4
112 months        11     0    15      0
113 % time        15     0   20.8     0
114 % draft      9.3   0.0   10.7   0.0
115
                                  CONTROL
```

Fig. 5.4 Examples of computer screens of the WAFLEX model

At nodes where there is a bifurcation or structure, the concentration is constant over the node. At a junction, however, two discharges with different concentrations of contaminants may meet:

$$Q_d c_d = Q_{u1} c_{u1} + Q_{u2} c_{u2} \tag{5.12}$$

reservoirs:

In a reservoir, the contaminant balance is somewhat more complicated. The rate of change of the quantity of contaminants equals the amount which entered the reservoir minus the amount that was discharged, per unit of time:

$$\frac{\mathrm{d}(Sc)}{\mathrm{d}t} = Ic_i - Oc \tag{5.13}$$

where c_i is the contaminant concentration of the entering water, and c is the concentration of the reservoir water. Elaboration yields:

$$\frac{\mathrm{d}c}{\mathrm{d}t} = \frac{-c\mathrm{d}S/\mathrm{d}t + Ic_i - Oc}{S} \tag{5.14}$$

The value of dS/dt can be substituted from Eq.(5.3), yielding:

$$\frac{\mathrm{d}c}{\mathrm{d}t} = \frac{I(c_i - c) - c(P-E)/A}{S} \tag{5.15}$$

In case the rainfall balances the evaporation ($P=E$) and if I/S may be considered constant with time (not such a valuable assumption, but acceptable for the purpose of illustration), then Eq.(5.15) can be integrated analytically, yielding:

$$c - c_i = (c_0 - c_i)\exp\left(-\frac{I}{S}(t - t_0)\right) \tag{5.16}$$

Hence the cleaning of a reservoir by flushing is an exponential process where the value c_i is only reached asymptotically.

water use points:

At a water consumption point, the contaminant balance reads:

$$c_d(Q_u - C) = c_u(Q_u - U) + c_R R \tag{5.17}$$

where c_R is the contaminant concentration of the drainage water (return flow). The other symbols have been defined earlier. If we assume that the drainage water contains all the contaminants which entered the user's system, then the concentration of the return flow should be:

System Component	Sub-component	Mathematical Description	Remarks
Branch	pipe	$c_d = c_u$	no loss
	canal	$c_d = c_u$	positive loss
	river	$c_d = c_u$ if $q > 0$	positive loss
		$c_d = (Q_u c_u + q \, \Delta x \, c_q)/Q_d$ if $q < 0$	negative loss
Node	junction	$c_d = (c_{u1} Q_{u2} + c_{u2} Q_{u2})/Q_d$	
	bifurcation	$c_d = c_u$	
	structure	$c_d = c_u$	
Reservoir		$dc/dt = [I(c_i - c) - c(P-E)/A]/S$	
Inflow point	sub-catchment	$c_i(t)$	
	well field	$c_i(t)$	
Offtakes	consumption point	$c_d = (c_u(Q_u - U) + c_R R)/(Q_u - C)$	
	downstream requirement	$c <$ criterion	

Table 5.2 System elements and the expressions to describe water quality

$$c_R = \frac{c_u U}{R} \tag{5.18}$$

Particularly in the case of irrigation, where the drainage water is supposed to leach the accumulated salts, this assumption is quite acceptable. In fact, if the return flow R would contain less conservative contaminants (in particular salts) than the withdrawal U, then the system would have been wrongly designed, allowing accumulation of salts in the fields, which results in a loss of productivity of the system.

In Fig. 5.5 is an illustration from the QUAFLEX model, which is the water quality daughter of WAFLEX

5.5. Integrated water resources system

Now that the system model (such as WAFLEX) incorporates the topographical locations of the water resources system, taking well into account whether an element lies upstream or downstream from other elements, the aspect of location, as defined in Section 3.4 has been taken care of.

Since the WAFLEX model both takes into account surface water resources and groundwater resources in the form of seepage from groundwater and well-fields, it integrates over the type of the resource.

Moreover, since the QUAFLEX version of WAFLEX incorporates the quality with regard to various contaminants or substances (according to Section 5.4), the simulation model may be called an integrated water resources system; such a model is a requirement for integrated planning.

This brings us to the aspects of integrated water management that we have not yet looked at: the integration over the relevant sectors of the economy; the integration over the national objectives and constraints; and the institutional framework. These aspects will be dealt with in the following lectures on Framework for Analysis and Management Arrangements.

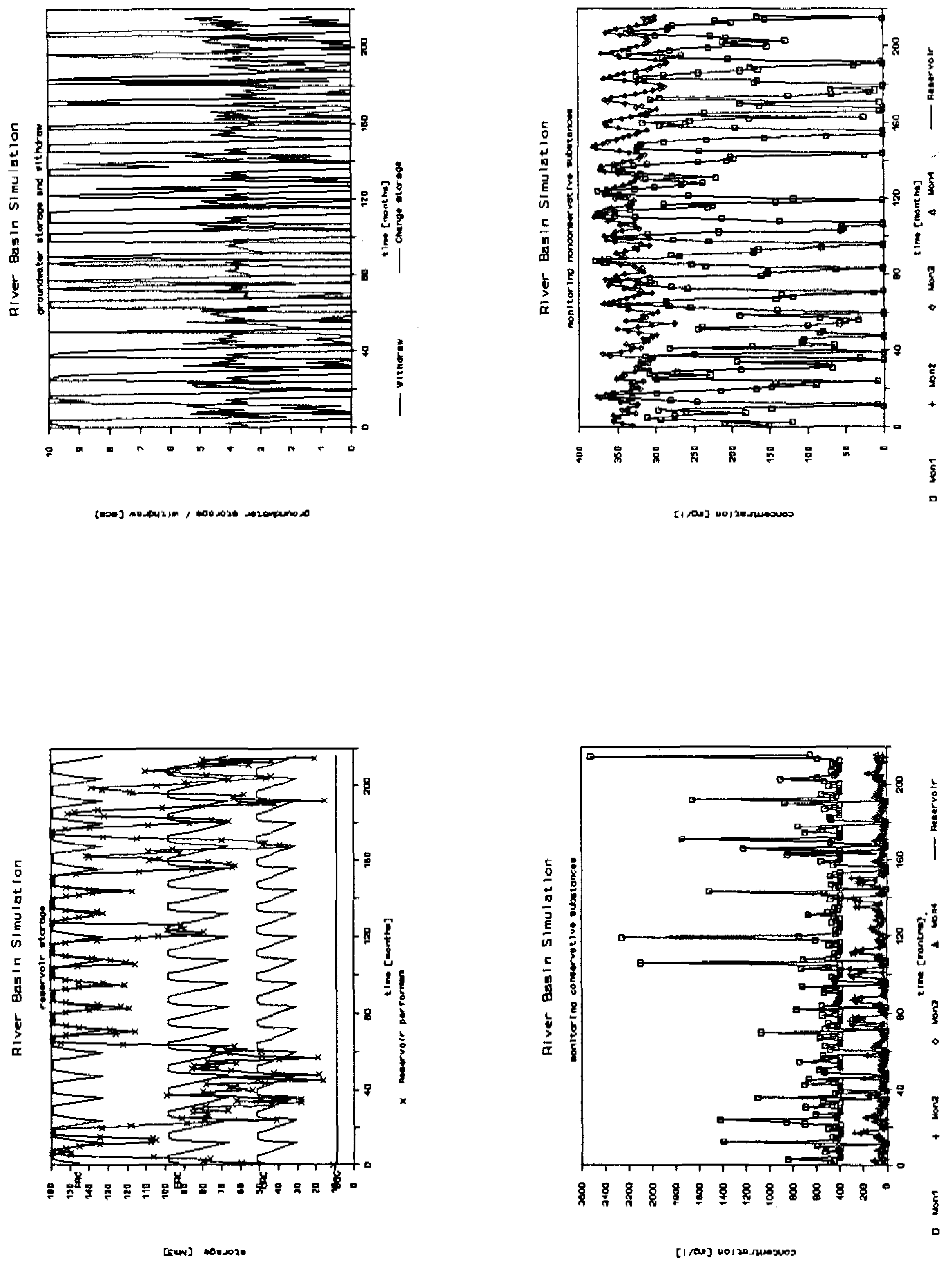


Fig. 5.5 Examples of computer screens of the QUAFLEX model for water quality

Exercises:

Reservoir Operation

A. Spreadsheet Model RESSIMOP

Run the programme Ressimop.wr1 under **Lotus Symphony**. The spreadsheet model corresponds with the mathematical model and with the steps outlined in Section 5.2.

The spreadsheet contains an Input range, graphical windows, a Hydrology range (where the inflow, the rainfall and precipitation are presented), a Manual, and a Computation range.

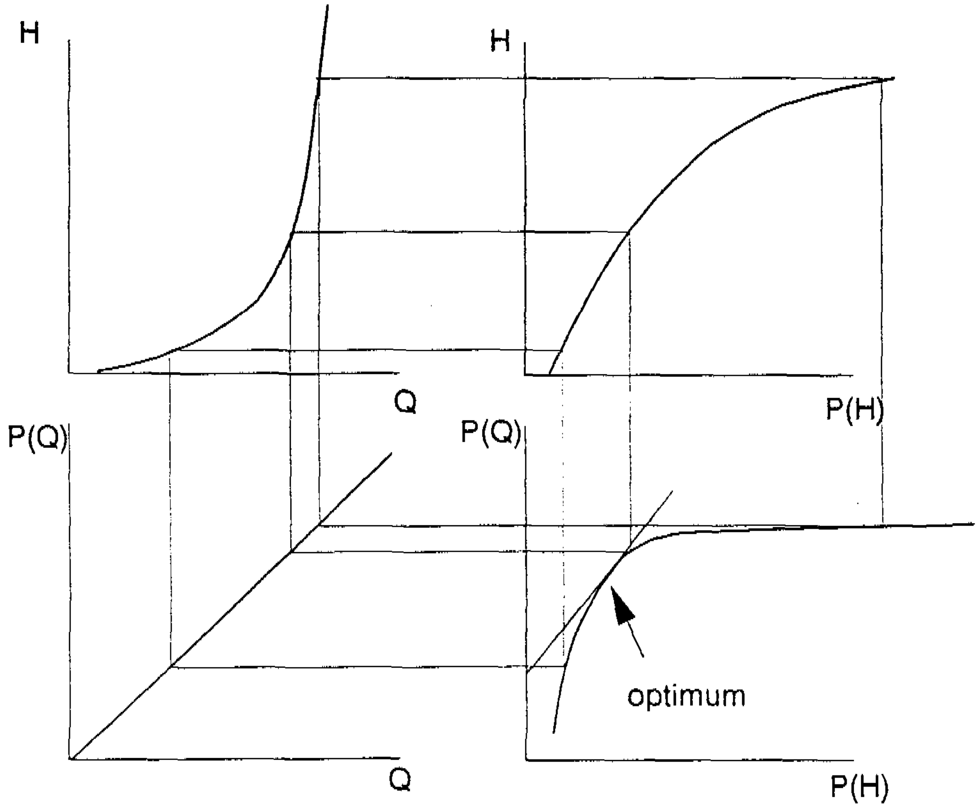
The model is operated through a Menu which is activated by pressing Alt M.

assignment

The engineer who *investigates the dimensioning of a future reservoir, wants to find* a relation between the draft D (the amount of water he can take from the reservoir) and the elevation of the crest H_c of the spillway (the height of the dam). He/she aims at an average reliability of the supply of 90% of the time, which means that he/she allows the system to fail during 10% of the time.

a.1. Find the relation between draft and elevation; try three crest levels: 185 m, 190 m, and 195 m, and adjust the draft until you get a reliability of approximately 90 %. Always make sure that the initial level in the reservoir equals the final level. (tip: start with a full reservoir, $H_0=H_c$).

a.2. How much is the maximum sustainable draft which can be taken from the reservoir, if it is assumed very large.



B. Spreadsheet Model RESSIMFL

Now that you have determined the height of the crest of the spillway, you need to determine the size of the spillway. The model Ressimfl has been made for that purpose. It works in much the same way as the model Ressimop, only it uses a much smaller time step (representative for a flood hydrograph) and the effect of direct rainfall on the reservoir can be neglected. It is based on the equations and on the steps outlined in Section 5.2.

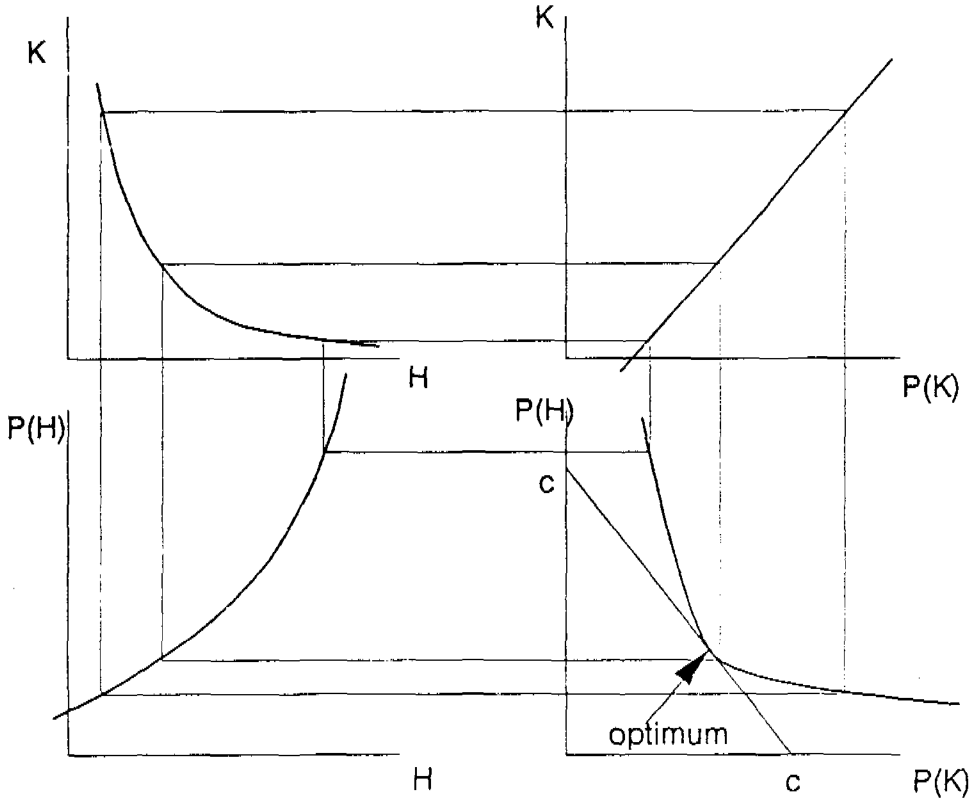
The model is organized similarly to Ressimop and it has a similar menu structure, which is activated by pressing Alt M.

assignment

The engineer now has to determine the size of the spillway. He has to make a trade-off between making a narrow spillway, which will result in a higher water level above the spillway and hence a higher dam, or making a wider spillway. In agreement with Eq.(5.7), it can be assumed that $K=1.5B$, where B is the width of the spillway.

b.1. Try out several values for K between 5 and 500 m and determine the highest water level H_{max} obtained with such a spillway.

b.2. Plot the values of K against H_{max}, what can you conclude?



Exercise: **WAFLEX**

The Cunapo catchment in Trinidad has two major tributaries: the Cunapo and the Oropuche. In the Quare river, a tributary to the Oropuche, a dam has been built: Hollis dam. It is a small dam in the upper catchment and it serves to supply the capital of Trinidad, Port of Spain, of water through a pipeline. Also there are several water users along the different branches of the river system.

The WAFLEX model simulates this system. There are a number of inflow (IN) and outflow (USE) points connected to the system. The four major water users are:

- USE1, an off-river pumping irrigation scheme on the Cunapo river;
- USE2, an off-river pumping irrigation scheme near Sangre Grande;
- USE3, the off-take downstream of Hollis reservoir for the water supply to Port of Spain;
- USE4, an off-river pumping scheme on the Oropuche river.

The off-takes at USE2 and USE3 are under the control of the reservoir, the others have to rely on unregulated flows.

Hollis reservoir has three operating rule curves:

- The flood rule curve FRC, which is a hard boundary; if the water level reaches the FRC, all water which enters the reservoir is spilled over the spill way.
- The utility rule curve URC, which is a soft boundary; if the water level reaches (or crosses) the URC, the release from the reservoir is reduced to a certain rationing percentage.
- The dead storage curve DSC, which is a hard boundary; the water level may never drop below this level due to releases, only due to evaporation.

In this exercise we are going to try to improve the management of the water resources by maximizing the outputs of the system under the constraints of preset reliabilities.

1) At Use, the farmers allow a failure of 25%. Find the corresponding amount of water they can pump from the river.
2) At USE, a failure of 10% is accepted. Find the corresponding amount that can be withdrawn from Hollis.
3) If we only take water from Hollis at USE3 during the wet season and take water from ground water resources near the city during the dry season, we can increase the amount of water taken from Hollis. Adjust the withdrawal pattern from Hollis so that during the first 5 months the requirement is 0, and find the new annual withdrawal amount that fails in 10% of the time
4) We can increase the reliability of the system, by changing the rationing that takes place when the level in the dam reaches the Utility Rule Curve (URC). Change the rationing to 20% and see what happens.

Exercise: Rainfall-Runoff modelling

Spreadsheet Model RAINRU

The spreadsheet programme RAINRU1.wr1 works under Lotus Symphony. It is based on the theory explained in Section 3.3. The lecture notes show the case of the Cunapo catchment in Trinidad.

When loaded, the model shows 5 windows, between which one can toggle by pressing the F6 key. To zoom into a window one presses Alt F6. One of the windows (window 3) is not in use.

The model is governed by a menu which can be activated by pressing Alt M. The option 'Input' moves the programme to the Input Screen.

The model is used to find the partial runoff coefficients b_i through multiple stepwise backward regression. Symphony has the multiple regression option in its statistical package.

The following steps are taken:

1. Load Symphony's statistical package by pressing Alt A. This should be done before the analysis is started.
2. Select the option Threshold from the menu.
3. In the first try, set the threshold in 0 mm/decade.
4. Carry out the multiple regression by selecting the option Regression from the menu.
5. Analyze the explained variance (r^2) obtained by increasing the memory of the system.
6. Check if an improvement can be obtained by including a threshold. (select Threshold, increase the threshold, select Regression).
7. Analyze the partial runoff coefficients obtained, try to attribute a physical meaning to them.
8. How can you explain the relatively high value of a?

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> The proceedings of the Delft Symposium where the concept of "Water Sector Capacity Building" was brought to the world's attention. It was recognised that the main impedient to sustainable development of water resources is not the technology but the lack of institutional and professional capacity in combination with an unfavourable policy environment. A strategy is presented for building this capacity, including: the creation of an enabling environment with appropriate policy and legal frameworks; institutional development, including community participation; and human resources development and strengthening of managerial capacity.

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> An excellent awareness raising document, with ample material to illustrate the water crisis that the world is facing in the coming years. The emphasis of the document is on the need for population control to reach sustainable levels of water use. It contains a very useful list for all the countires in the world of their per capity water availablity now and in the future.

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The first document to launch the concept of sustainable development world wide. The main focus of the book is on population, food, biodiversity, energy and industry. However, the word water hardly appears in the document, and when it does, it is in relation to urban water supply. The availability of water resources was certainly not addressed as one of the main constraints for sustainable development. Nevertheless, the book is a classic.

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