INTERNATIONAL HYDROLOGICAL PROGRAMME

Coping with water scarcity

by

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1. Introduction

Water scarcity is among the main problems to be faced by many societies and the World in the XXI century. Water scarcity is commonly defined as a situation where water availability in a country or in a region is below 1000 m^3 per person per year. However, many regions in the World experience much more severe scarcity, living with less than 500 m^3 per person per year, which could be considered severe water scarcity. The threshold of 2000 m^3 per person per year is considered to indicate that a region is water stressed since under these conditions populations face very large problems when a drought occurs or when man-made shortages are created. However, the concept of water availability based on indicators driven from the renewable water resources divided by the total population should be taken with great care. This simple indicator may not be very meaningful in situations where countries make high use of desalination, of non-renewable groundwater resources and of wastewater re-use to compensate for their scarcity of renewable water. This may also be true for countries where irrigation water requirements are not large.

Water scarcity causes enormous problems for the populations and societies. The available water is not sufficient for the production of food and for alleviating hunger and poverty in these regions, where quite often the population growth is larger than the capability for sustainable use of the natural resources. The lack of water does not allow industrial, urban and tourism development to proceed without restrictions on water uses and allocation policies for other user sectors, particularly agriculture. Natural fresh water bodies have limited capacity to respond to increased demands and to receive the pollutant charges of the effluents from expanding urban, industrial and agricultural uses. In regions of water scarcity the water resources are probably already degraded, or subjected to processes of degradation in both quantity and quality, which adds to the shortage of water. Health problems are commonly associated with scarcity, not only because the deterioration of the groundwater and surface waters favours water borne diseases, but because poverty makes it difficult to develop proper water distribution and sewerage systems. Water conflicts still arise in water stressed areas among local communities and between countries since sharing a very limited and essential resource is extremely difficult despite legal agreements. Poverty associated with water scarcity generates migratory fluxes of populations within countries or to other countries where people hope to have a better life, but where they may not be well received. Last, but not least, water for nature has become a low or very low priority in water stressed zones. Preserving natural ecosystems is often considered a superfluous use of water compared with other uses that directly relate to healthy human

life, such as domestic and urban uses, or that may lead to the alleviation of poverty and hunger, such as uses in industry, energy and food production. However, the understanding that natural ecosystems, namely the respective genetic resources, are useful for society is growing, and an effort to protect reserve areas is already developing, even in water scarce regions.

Regions where water has been always scarce gave birth to civilisations that have been able to cope with water scarcity. These societies developed organisational and institutional solutions and water technologies and management skills within the local cultural environment that allowed for appropriate water use for domestic, food production and local industrial purposes. Lifestyle and development changes during the last decades created new needs for water, provided contradictory expectations on cultural and institutional issues, and led to very strong increases on the demand for water. The existing balances between demand and supply were broken and new equilibria are required, mainly through the use of modern technologies and management tools which must be adapted to the local culture, environment, and institutions. Finding such new equilibria is the challenge for the societies living in water stressed areas, and for professionals in a multitude of scientific and technological domains, which impinge on the cultural, social and environmental facets of water resources. To explore some of the issues that may help in finding and implementing such equilibria to cope with water scarcity is the objective of this book.

The book intends to serve as a guide, not to be followed as such, but to serve for establishing regional or local guidelines oriented to help in developing and implementing new conceptual and managerial ideas that may assist in coping with water scarcity. The basic idea behind the book is that water scarcity will continue to exist and, for many regions, unfortunately will continue to grow. Human and societal skills will need to be developed to cope with water scarcity and to assist the local people to live in harmony with the environmental constraints, particularly those concerning water resources. This guideline does not produce an exhaustive review on every aspect covered but attempts to provide basic information to assist decision-makers, water managers, engineers, agronomists, economists, social scientists and other professionals to have coherent and hopefully harmonious consolidated views on the problems. Therefore, to help assist those who may need more detail, oriented, but less than comprehensive bibliographies are given.

A range of concepts relevant to water scarcity are first discussed. Natural and man-made water scarcity are first defined. Natural scarcity usually results from arid and semi-arid climates and drought, whereas man-made scarcity is associated with desertification and water management. This approach brings into focus the effects of water quality as well as water quantity on water scarcity. For example degradation of water quality makes unavailable a resource that otherwise could be available. The consideration of desertification shows how water scarcity can bring about the impoverishment of the land and other natural resources due to erosion, salinisation and loss of fertility caused by human activities and climate variation in arid to sub-humid climates. This conceptual approach implies that measures and practices to cope with water scarcity need to be related to the causes, and therefore to the actual problems prevailing in any given region. An introductory discussion of the respective water management issues and implications for sustainable development are consequently presented.

The physical characteristics and processes leading to water scarcity complement the

discussion of concepts. Climatic conditions dominant in water scarce regions are analysed, particularly rainfall variability and evaporation. The essential hydrologic characteristics are briefly reviewed, referring to the runoff regimes prevailing in water stressed regions, the processes affecting groundwater recharge and availability, and sediment loads and water quality, including those aspects leading to desertification and water-shortage. Special reference is made to droughts, particularly concerning definitions and the possibilities of forecasting. Also included are references to the need for data collection, data quality assessment and use of data handling and archiving techniques so that data are readily available for planning and management studies.

There is also an in-depth examination of conceptual thinking in coping with water scarcity. This is oriented to provide a basis for innovation in examining the value of water in conditions of water scarcity, to encourage different thinking in assessment of the social, environmental and economic values of water and to consequently establish appropriate priorities for water allocation and use, taking such values into account.

Ideas for maximising the availability of surface water for human use are proposed. These ideas are presented to support planning and management initiatives to provide more water for domestic or industrial supply or for crop growth for production of food and fibre. These refer to both large and small scale projects, including water harvesting. Particular attention is given to reservoir management. The need for reservoirs in water scarce regions is well known despite the controversy surrounding the environmental impacts of river dams in less stressed environments. Requirements for water scarcity management, relative to operation of single and multiple reservoir systems, including for groundwater recharge, as well as implications for design and management of water resource systems are discussed. Attention is called to the control of water losses and non-beneficial uses of water, particularly concerning the detection of losses, the reduction of evaporation, and the encouragement needed for reduction of wastes. Water harvesting as a main tool for rainfall and runoff conservation in arid and semiarid zones is reviewed under a variety of situations, such as rainwater collection, and use of terracing, small dams and tanks, runoff enhancement, runoff collection, flood spreading, and water holes and ponds. The environmental issues relative to surface water storage and use are also discussed, embracing the protection of stored water, the control of sediments and water quality, the impacts on the riparian ecosystems and combat of water borne diseases.

Principal aspects of groundwater use and recharge are reviewed in the perspective of achieving sustainable groundwater development, i.e. avoiding groundwater degradation. The analysis concerns both major aquifers and well fields and minor aquifers of local importance, such as in islands. It includes brief reviews on groundwater reservoir characteristics, their conditions for discharge, replenishment and storage, issues for exploitation and management, as well as requirements for aquifer monitoring and control and maintenance of wells, pumps and other facilities. Attention is paid to the effects and environmental impacts of aquifer over-exploitation upon groundwater levels, energy costs for pumping, water quality deterioration resulting from sea water intrusion, land subsidence, reduction of surface stream base-flow, drying of wetlands and impacts on landscapes. Also attention is given to artificial recharge needs and methods, and related problems and solutions, particularly environmental impacts. The need for conjunctive use of surface- and groundwater is analysed.

Taking account of its importance in water scarce regions, the use of non-conventional water resources to complement or replace the use of usual sources of fresh water is discussed. The use of wastewater is considered, mainly for irrigation purposes, but other less stringent uses such as for aquaculture are mentioned. Attention is paid to the need to know the characteristics of wastewater and effluents, and particularly of the possible occurrence of toxic substances and pathogens in wastewaters.

The examination pays particular attention to the control of health risks for both consumers and workers, and so it includes an overview on wastewater treatment measures and practices used to minimise health hazards, and issues in monitoring and control for safe wastewater use. Another resource important for irrigation in water scarce regions is saline water. As for wastewaters, the need to know the characteristics and impacts of saline waters is stressed, together with a need to adopt appropriate criteria and standards for assessing the suitability of that water for irrigation. Related practices for crop irrigation management, including leaching requirements to control the impacts on soil salinity as well requirements for monitoring and evaluation are discussed. The use and treatment of desalinated water for non-agricultural uses are also analysed. Other non-conventional uses considered are fog water capture, water harvesting, groundwater harvesting, cloud seeding, and water transfers

Water conservation and water saving practices and management constitute a central, extended part of this book, consisting of technical guidelines oriented to practice. The importance of water conservation and water savings in coping with water scarcity is reviewed, considering particularly the scarcity conditions result from aridity, drought, desertification and man induced water shortage. The main concepts relative to water use, consumptive use and water losses are discussed prior to the introduction of the topics of water conservation, water saving practices and management issues. These refer to uses in urban areas, domestic water uses, landscape and recreational uses, industrial and energy uses, and rain-fed and irrigated agriculture. Essentially they focus on demand reduction and water waste control practices and tools. Complementarily, supply management is discussed concerning management measures that provide for operation and water allocation aiming at higher system performances and reduced impacts of water saving on users. An overview of water conservation and saving under severe water scarcity conditions, such as may occur during drought completes this technical subject.

Complementing the engineering aspects referred above, the social, economic, cultural, legal and institutional constraints and issues are discussed as oriented to local communities, urban centres, rural areas, user groups, and administrative, public and private organisations which are concerned with water supply.

The educational aspects constitute the last part of this guide. The main purpose of education is to change people's attitudes to water. Therefore the focus of the discussion is to consider how attitudes can be changed and how an educational program may be established. Education is meant in the widest sense, aimed at children and youths, women, with their role in the family and the community, farmers and industrial water users, managers, operational and maintenance personnel, educators, agronomists and engineers. The need for innovation in developing public awareness of water scarcity issues is also stressed.

2. Water scarcity concepts

2.1.Water scarcity concepts

2.1.1. Introduction

At the beginning of the XXI century, the sustainable use of water is not only a priority question for water scarce regions and for agriculture in particular, but for all sectors and regions. Imbalances between availability and demand, degradation of surface and groundwater quality, inter-sectorial competition, inter-regional and international conflicts, all bring water issues to the foreground.

Decades ago, water was viewed as a non-limited natural resource because it was renewed every year in the course of the seasons. Man progressively appropriated this resource and used it with few restrictions. Developments in controlling and diverting surface waters, exploring groundwater, and in using the resources for a variety of purposes have been undertaken without sufficient care being given to conserving the natural resource, avoiding wastes and misuse, and preserving the quality of the resource. Thus, nowadays, water is becoming scarce not only in arid and drought prone areas, but also in regions where rainfall is relatively abundant. Scarcity is now viewed under the perspective of the quantities available for economic and social uses, as well as in relation to water requirements for natural and man-made ecosystems. The concept of scarcity also embraces the quality of water because degraded water resources are unavailable or at best only marginally available for use in human and natural systems.

Worldwide, agriculture is the sector which has the highest demand for water. As a result of its large water use irrigated agriculture is often considered the main cause for water scarcity. Irrigation is accused of misuse of water, of producing excessive water wastes and of degrading water quality. However, irrigated agriculture provides the livelihood of an enormous part of the world rural population and supplies a large portion of the world's food. At present, irrigated agriculture is largely affected by the scarcity of water resources. Efforts from funding agencies and managers are continuously providing incentives to innovate and develop management practices to improve water management, to control the negative impacts of irrigation, to diversify water uses in irrigation projects, and to increase yields and farmers incomes. Similarly, great progress in engineering and economic management are producing new considerations for water use and water quality control for non agricultural purposes, particularly for domestic consumption and sanitation.

The sustainable use of water implies resource conservation, environmental friendliness, technological appropriateness, economic viability, and social acceptability of development issues. The adoption of these sustainability facets is a priority for using water in every human, economic and social activity –human and domestic consumption, agriculture, industry, energy production, recreational and leisure uses – particularly in water scarce regions. The perception that water is increasingly scarce gives to water management a great relevance.

2.1.2. Causes for water scarcity

Water scarcity may result from a range of phenomena. These may be produced by natural causes, may be induced by human activities, or may result from the interaction of both, as indicated in Table 2.1. (cf. Vlachos and James, 1983).

TABLE 2.1. Nature and causes of water scarcity in dry environments.

Water Scarcity Regime	Nature produced	Man induced
Permanent	**Aridity**	**Desertification**
Temporary	**Drought**	**Water shortage**

Aridity *is a natural permanent imbalance in the water availability consisting in low average annual precipitation, with high spatial and temporal variability, resulting in overall low moisture and low carrying capacity of the ecosystems.*

Aridity may be defined through climatological indices such as the Thornthwaite moisture index, the Budyko radiation index of dryness, or the Unesco precipitation/evapotranspiration index (Sanderson, 1992). Under aridity, extreme variations of temperatures occur, and the hydrologic regimes are characterised by large variations in discharges, flash floods and large periods with very low or zero flows.

Drought *is a natural but temporary imbalance of water availability, consisting of a persistent lower-than-average precipitation, of uncertain frequency, duration and severity, of unpredictable or difficult to predict occurrence, resulting in diminished water resources availability, and reduced carrying capacity of the ecosystems.*

Many other definitions of drought exist (Yevjevich, 1967; Wilhite and Glantz, 1987; Tate and Gustard, 2000). The U. S. Weather Bureau defined drought (Dracup *et al*., 1980) as a lack of rainfall so great and so long continued as to affect injuriously the plant and animal life of a place and to deplete water supplies both for domestic purposes and the operation of power plants, especially in those regions where rainfall is normally sufficient for such purposes. Generally, these definitions clearly state that drought is mainly due to the break down of the rainfall regime, which causes a series of consequences, including agricultural and hydrological hazards which result from the severity and duration of the lack of rainfall.

It is important to recognise the less predictable characteristics of droughts, with respect to both their initiation and termination, as well as their severity. These characteristics make drought both a hazard and a disaster. Drought is a hazard because it is a natural accident of unpredictable occurrence but of recognisable recurrence. Drought can

be a disaster because it corresponds to the failure of the precipitation regime, causing the disruption of the water supply to the natural and agricultural ecosystems as well as to other human activities.

Desertification *is a man-induced permanent imbalance in the availability of water, which is combined with damaged soil, inappropriate land use, mining of groundwater, and can result in increased flash flooding, loss of riparian ecosystems and a deterioration of the carrying capacity of the ecosystems.*

Soil erosion and salinity are commonly associated with desertification. Climate change also contributes to desertification, which occurs in arid, semi-arid and sub-humid climates. Drought strongly aggravates the process of desertification by increasing the pressure on the diminished surface and groundwater resources. Different definitions are used for desertification, generally focusing on land degradation, as it is the case of the definition proposed by the United Nations Convention to Combat Desertification: land degradation in arid, semi-arid and dry sub-humid zones resulting from various factors including climatic variations and human activities. In this definition land is understood as territory and is not restricted to agricultural land since desertification causes and impacts do not relate only with the agricultural activities but are much wider, affecting many human activities, nature and the overall living conditions of populations. However, these definitions need to be broadened in scope to focus attention on the water scarcity issues. When dealing with water scarcity situations, it seems more appropriate to define desertification in relation to the water imbalance produced by the misuse of water and soil resources, so calling attention to the fact that the misuse of water is clearly a cause of desertification.

Different definitions are used for desertification, mainly focusing on land degradation and sometimes not referring to water. However, when dealing with water scarce situations it seems more appropriate to define desertification in relation to the water and nature imbalances produced by the misuse of water and land resources, thus calling attention to the fact that desertification, including land degradation, definitely is a cause for water scarcity.

Water shortage *is also a man-induced but temporary water imbalance including groundwater and surface waters over-exploitation, degraded water quality and is often associated with disturbed land use and altered carrying capacity of the ecosystems.* For example withdrawals may exceed groundwater recharge, surface reservoirs may be of inadequate capacity and land use may have changed, revising the local ecosystem and altering the infiltration and runoff characteristics. Degraded water quality is often associated with water shortages and exacerbates the effects of water scarcity. There is no widely accepted definition for this water scarce regime and the term “water shortage” is often used synonymously with water scarcity. However it is important to recognise that water scarcity can result from human activity, either by over-use of the natural supply or by degradation of the water quality. This man-induced water scarcity is common in semi-arid and sub-humid regions where population and economic forces may make large demands on the local water resource, and where insufficient care is taken to protect the quality of the precious resource.

2.1.3. Aridity and drought water scarcity

In terms of water management, regions having dry climates due to natural aridity are often not distinguished from drought prone areas. This rough approximation of definitions can be misleading in water management.

In arid regions rainfall is low all the year around and is particularly lacking during the dry season, which may last for several months. The natural vegetation and ecosystems may be of the desert or steppe type in arid zones, or of savannah and chaparral types in semiarid zones. Rain-fed agriculture is uncertain in arid climates, but is generally viable under semi-arid conditions, especially when the use of rainfall is maximised, as for winter grain and fodder crops. However, to achieve higher yields and to produce vegetables and food and fiber cash crops in these climatic conditions, irrigation is required. Irrigation in arid and semi-arid zones has been practised for millennia, supporting ancient civilisations in very densely populated areas of the world.

Peoples and nations in arid areas developed appropriate skills to use and manage water in a sustainable way. These included measures to avoid waste of water, the adoption of technologies appropriate to the prevailing conditions, making successful use of water for agriculture and other productive activities, and the development of institutional and regulatory conditions that largely influenced the behaviour of rural and urban societies. These adaptations to live with limited water availability also included measures and practices to cope with extreme scarcity conditions when drought aggravated the limited water supplies. In the civilisations that survived the present conditions correspond to an integration of a strong cultural heritage with modern management, engineering, social and institutional practice to respond to the challenges of development. This integration is not yet totally satisfactory due to the contradictory forces of progress, and thus innovative thinking is required to make development sustainable.

Water scarcity due to drought needs appropriate approaches. To successfully cope with drought there is a need to understand the characteristics and consequences of those phenomena which make water scarcity due to drought very different from that caused by aridity. Dealing with water scarcity situations resulting from aridity usually requires the establishment of engineering and management measures that produce the conservation and perhaps the seasonal augmentation of the available resource. On the other hand droughts require the development and implementation of preparedness and emergency measures.

Differences in the perception of drought lead to the adoption of different definitions, which do not have general acceptance, nor have worldwide applicability, as reviewed by Wilhite and Klantz (1987) and Tate and Gustard, (2000). The controversy over perceptions of drought, and the consequent defining of them and their characteristics, do not help decision and policy makers to plan for droughts. Lack of clearly agreed definitions make it difficult to implement preparedness measures, to apply timely mitigation measures when a drought occurs, or to adequately evaluate drought impacts.

Several authors point out that scientists, engineers, professionals, decision-makers often do not agree on whether to regard drought as a hazard or as a disaster. As stated by Grigg and Vlachos (1990), this difference in perception is one of the central problems of water management for drought. As discussed above, drought is a hazard and a disaster. It is a hazard because it is a natural incident of unpredictable occurrence, and it is a disaster,

because it corresponds to the failure of the precipitation regime, causing disruption of water supply to the natural and agricultural ecosystems as well as to human and social activities.

The perception of the hazardous nature of dependence on precipitation and water availability depends on the climatological, meteorological and hydrological regimes of the affected region, as well as on the severity of the effects. In humid climates a short period without rainfall may be considered a drought, while in an arid or semiarid environment a dry period with the same duration could be considered normal.

The characterisation of a drought using indices is also controversial and often contradictory. It is common that agronomists use the word drought to define a water stress condition affecting crop growth and yield (Maracchi, 2000). Drought could then be characterised by a crop-water stress index (e.g. Petrasovits, 1990). Short duration dry periods for agricultural are not considered to be droughts in this publication, but are defined as dry spells. These are characteristic of sub-humid temperate and tropical climates, and may cause relatively long periods of low soil moisture for introduced agricultural activities. However they have less impact on natural ecosystems and on other human activities.

Some authors prefer to adopt an operational definition that distinguishes between meteorological, agricultural, and hydrological droughts. These usually focus on the indicator variable of prime interest, which could be the precipitation (meteorological drought), soil moisture (agriculture drought), stream flow discharges or groundwater levels (hydrological drought and groundwater drought). Alternative definitions result from the complexity of the hydrological process that controls the temporal and spatial distribution of rainfall via the various paths within the large-scale hydrological cycle and the global circulation of the atmosphere. In certain regions, where water supplies mainly depend upon river diversions, when dealing with a regional drought it may be necessary to consider not only precipitation but also stream-flow. However, stream flow is also a dependent variable, controlled by the current and antecedent precipitation. In many cases, where the river discharges are regulated by dams and other hydraulic structures, the drought definition may need to be more a reflection of the river management decisions than of the natural supply. Thus, the use of precipitation or stream-flow data may not be sufficient to characterise droughts at the local scale, but the definition may need to reflect the supply conditions at the river basin scale.

The interdependence between climatic, hydrologic, geologic, geomorphic, ecological and societal variables makes it very difficult to adopt a definition that fully describes the drought phenomena and the respective impacts. Meteorologists and hydrologists have developed indices, which depend on hydrometeorological parameters or rely on probability. Several drought studies (e.g. Yevjevich *et al*., 1983; Wilhite *et al*., 1987; Vogt and Somma, 2000) give examples of these indices.

The definition adopted herein accommodates a variety of conditions and corresponds to the concepts of both hazard and disaster. That definition also allows a clear distinction between drought and the other water scarce regimes defined above (see Vlachos and James, 1983; Pereira, 1992).

2.2. Coping with water scarcity

2.2.1. Main problems in brief

In most regions of the world, the annual withdrawal or use of water is a relatively small part (less than 20%) of the total annual internally renewable water resources (Table 2.1). In water scarce regions, as is the case for the Middle East and North Africa regions, that share averages 73% of the total water resources (The World Bank, 1992). In these regions 53% of the per capita annual withdrawals for all uses including irrigation are below 1000 m^3/ca and 18% between 1000 and 2000 m^3/ca. In Sub-Saharan countries, 24% of the population lives in areas where annual withdrawals are below 2000 m^3/ca and 8% below 1000 m^3/ca. More recent appraisals confirm the relevancy of the problem (e.g. Shiklomanov, 1998, 2000). The relevancy of the problems of water scarcity is evidenced when considering that estimates for the average annual growth of the population are the World's highest in the same regions: 2.9% for 1990-2000 and 2.3% for 2000-2035 for Middle East and North Africa, and 3.0% and 2.4% for the same periods in Sub-Saharan Africa (Table 2.2). Forecasts for next 30 years show that water scarcity or water stress may affect a very large number of countries (e.g. Engelmann and LeRoy, 1993).

TABLE 2.2. World availability of water Resources (source: The World Bank, 1992).

Country Group	Total annual internal renewable water resources (10^6 m^3)	Total annual water withdrawal (10^6 m^3)	Annual withdrawal as a share of total water resources (%)	Per capita annual internal renewable water resources, (m^3)	Sectorial withdrawal as a share of total water resources		
					Agricult. (%).	Domestic (%)	Industry (%)
Low and middle income	28,002	1,749	6	6,732	85	7	8
Sub-Saharan Africa	3,713	55	1	7,488	88	8	3
East-Asia and Pacific	7,915	631	8	5,009	86	6	8
South Asia	4,895	569	12	4,236	94	2	3
Europe	574	110	19	2,865	45	14	42
Middle East and North Africa	276	202	73	1,071	89	6	5
Latin America and the Caribbean	10,579	173	2	24,390	72	16	11
High income	8,368	893	11	10,528	39	14	47
OECD members	8,365	889	11	10,781	39	14	47
Other	4	4	119	186	67	22	12
World	40,856	3,017	7	7,744	69	9	22

Agriculture takes the highest share among water user sectors in low-and middle-income countries, while industry is the most important user in developed countries in temperate and humid climates. Agriculture withdraws more than 85% of water in the average African, Asian and Pacific countries (e.g. Chaturvedi, 2000). This is a very high share which means there is a need for appropriate management. Irrigated areas have grown as much as 4 to 5 million hectares a year (Rangeley, 1990). This corresponds to an average growth rate of almost 2% a year since 1960 (Waggoner, 1994). However, this trend has

declined to near 1% during the 90's (Jensen, 1993) and less for the last decade. This growth is justified by the productivity of irrigated agriculture: irrigated areas represent about one-sixth of arable land but provide about one-third of the world's crop production (Waggoner, 1994). Expansion of irrigated areas occurred when crop yields also increased dramatically due to a combination of factors: improved irrigation techniques, high yield varieties and higher rate use of fertilisers, but in arid and semi-arid regions these last improvements could only be successfully introduced in irrigated areas. However, the expansion of irrigation has been achieved with several negative environmental impacts, namely waterlogging and salt affected soils (Jensen, 1993). Arid and semi-arid water stressed areas are particularly sensitive to these detrimental effects (Agnew and Anderson, 1992). Controlling environmental effects and increasing the performances are among future issues for water resources management (Hennessy, 1993; Pereira *et al*., 1996).

TABLE 2.3. Population and average annual growth (source: The World Bank, 1992).

Country Group	Population (millions)					Average annual growth (percent)				
	1973	1980	1990	2000	2030	1965-73	1973-80	1980-90	1990-00	2000-30
Low and middle income	2,923	3,383	4,146	4,981	7,441	2.5	2.1	2.0	1.9	1.4
Sub-Saharan Africa	302	366	495	668	1,346	2.7	2.8	3.1	3.0	2.4
East-Asia and Pacific	1,195	1,347	1,577	1,818	2,378	2.6	1.7	1.6	1.4	0.9
South Asia	781	919	1,148	1,377	1,978	2.4	2.4	2.2	1.8	1.1
Europe	167	182	200	217	258	1.1	1.2	1.0	0.8	0.6
Middle East and North Africa	154	189	256	341	674	2.7	3.0	3.1	2.9	2.3
Latin America and the Caribbean	299	352	433	516	731	2.6	2.4	2.1	1.8	1.2
High income	726	766	816	859	919	1.0	0.8	0.6	0.5	0.2
OECD members	698	733	777	814	863	0.9	0.7	0.6	0.5	0.2
World	3,924	4,443	5,284	6,185	8,869	2.1	1.8	1.7	1.6	1.2

Water quality is an expanding problem. Surface waters are becoming more polluted (low dissolved oxygen and increased fecal coliforms) in developing countries, but this trend being reversed in high income countries (The World Bank, 1992). Data on groundwater pollution only covers selected regions in the world. Similarly for nitrate contamination, which is more important in developed countries, data is only available for a few regions (Bogárdi and Kuzelka, 1991). By contrast, problems resulting from increased salinisation of aquifers are requiring increased attention in less developed regions in arid zones (Saad *et al*., 1995). Health problems are particularly acute. 900 million people are affected by diarrhoea each year. The World Bank (1992) estimates that water supply and sanitation improvements would decrease mortality from diarrhoea by 16% due to improvements in water quality, by 25% due to increased availability of water, by 37% where both improvements can be made and by 22% where proper disposal of excreta can be effected. Several other diseases are related to water like malaria, filarasis and bilharziasis (schistosomiasis) (Birley 1989; Tiffen, 1989; Hespanhol, 1996). These problems are common in water scarce regions and bring into clear focus the need for availability of safe water and sanitation.

2.2.2. Water management issues

Policies and practices of water management under water scarcity must focus on specific objectives according to the causes of water scarcity. An integrated technical and scientific approach is essential to develop and implement the management practices appropriate to deal with water scarcity. Policies and practices must be based on the assumption that water will not become abundant, so that water management policies and practices have to be specific for water scarcity, i.e. for man to cope with the inherent difficulties.

To cope with water scarcity means to live in harmony with the environmental conditions specific to and dictated by limited available water resources. For millennia, civilisations developed in water scarce environments and the cultural skills that made it possible to live under such conditions are an essential heritage of those nations and peoples. Progress in XX century often questioned traditional know-how, which has in some situations been replaced by modern technologies and management rules directly imported from other areas having different physical and social environments. Water consumption and demand has increased everywhere for domestic and urban uses, for agriculture and irrigation, for industry and energy production, and for recreation and leisure. However, these increases became particularly evident in regions where water is scarce or, at least, not abundant. Therefore, man made dry regimes are now adding to the natural water scarce conditions, in many cases aggravating the existing situation.

Solving water management problems that are faced in water scarce regions calls for innovative approaches to cope with water scarcity. Innovation includes the adaptation of traditional know-how to the current day challenges, the adaptation of the externally available technologies to the prevailing physical and social conditions, and the creation of new and well adapted technologies and management approaches. Innovation must be used to assist man to cope with the environmental constraints and engineering and managerial solutions must be found that are specific to the existing causes for water scarcity: nature produced aridity and drought, and man induced desertification and water shortage.

***Aridity*:**

Among other characteristics, aridity is very often associated with:

- population growth that is above the capacity of support of the available natural resources, water in particular,
- high pressure on natural resources, producing their progressive degradation,
- strong competition for water for human, economic, and social uses, more recently including those of a recreational and leisure nature,
- water is the limiting resource for development, particularly for agriculture and food,
- vulnerable and fragile natural ecosystems,
- the soil resource is often degraded by erosion and salinity hazards, which are aggravated by poor agricultural water management,
- poverty and low educational levels of the populations threaten development.

Therefore, the sustainable use of water resources under aridity, implies:

- the effective adoption and implementation of integrated land and water resources planning,

- the improvement of water distribution and irrigation systems to achieve an increased service performance, which would induce efficient water use and production,
- the adoption of water allocation policies favouring reduced demand, conservation and efficient use,
- valuing the water as an economic, social and environmental good, including for nature conservation,
- measures for augmenting the available water resource, including waste water and drainage water re-use, conjunctive use of water from different origins, and the use of low quality and saline water,
- the adoption of appropriate water and irrigation technologies that favour water productivity and contribute to avoidance of water wastes and losses,
- innovative institutional and legal measures, including the transfer of responsibilities to users' associations,
- the users participation in water resources planning and systems management,
- education and training of water managers, operators and users,
- increased public awareness of water, soil and ecological conservation.

Drought:

Water management under drought requires measures and policies which are common with aridity, such as those to avoid water wastes, to reduce demand and to make water use more efficient. However other possible measures are peculiar to drought conditions and may be beyond the scope of the more common water management issues and policies. The peculiar characteristics of droughts may require use of specific measures. The complexity and hazardousness of droughts make their management particularly difficult and challenging.

Drought phenomena, including their causes, impacts, and other characteristics are often not well understood. The perception of a drought is different according to the activities affected and the disciplines professions and groups impacted by the drought. Forecasting of when a drought is likely to begin or to come to an end is extremely difficult. However, important progress is being made in relation to the possibilities of using the El Niño Southern Oscillation (ENSO) and, to a lesser degree, the North Atlantic Oscillation (NAO) as forecasting tools. Examples are given e.g. in Vogt and Somma (2000). Case studies relative to USA and Australia are analysed by Le Comte (2000) and Power (2000).

Droughts have a slow initiation and they are usually only recognised when the drought is already established. They are of long duration, and usually affect large areas. Their impacts are pervasive. Implementing drought control or drought preparedness measures and policies are receiving limited political attention in a changing economic and social environment, where growing pressures on natural resources, and development of man-induced water stressed conditions are creating new priorities. Nevertheless, drought aggravates these problems and diminishes the carrying capacity of the ecosystems.

The vulnerability of agricultural activities to drought have not decreased but have increased both in developed and less developed countries. In less developed countries food shortages have become much more frequent.

A better understanding of droughts is essential to develop tools for prediction or forecasting of drought initiation and ending, so that these occurrences may be clearly recognised. This is essential for timely and appropriate implementation of measures to cope with a drought. Planning for droughts tends not to receive priority attention of decision and policy makers because drought has diverse impacts. The slow initiation and undefined end of a drought makes it difficult to select the opportunity to take defensive or remedial action. When a flood occurs every symptom is obvious and opportune measures can be taken, usually with the support of public opinion since the disaster is easily recognised by all. In the case of a drought the disaster elements only become evident much later, when the drought has already started. Then the impacts last for a long time after the drought has ended, particularly if the lack of preparedness helped to turn the disaster into a catastrophe. Avoiding such problems requires appropriate monitoring, and for effective drought watch systems be implemented. Drought warning then becomes possible (Wilhite *et al*., 2000; Rossi, 2002).

Difficulties on predicting droughts are well known. Nevertheless, an adequate lead-time - the period between the release of the prediction and the actual onset of the predicted hazard - is more important than the accuracy of the prediction (Easterling, 1989). It is the lead-time that makes it possible for decision and policy makers to implement policies and measures to mitigate the effects of drought. In the case of agriculture several months lead-time is essential to make it possible for farmers to take decisions to alter crop and agricultural systems to cope with drought.

Difficulties in prediction have lead some to develop early warning indices (Wilhite *et al.*, 1987, 2000). These indices can be of a meteorological or hydrological nature, combining actual and time series data, with different degrees of sophistication in statistical treatment; or they may result from stochastic treatment of reservoir volumes (Rossi, 2002). Real-time agroclimatological networks can support early warning. Early warning does not provide as long a lead-time as prediction. Nevertheless it definitely helps with the timeliness of decisions.

Researchers face, therefore, a challenge for developing prediction and early warning skills appropriate to the climatic and agricultural conditions prevailing in different drought prone areas. Institutional arrangements are also needed to provide the links between data collection, data treatment, the research, and the potential users and decision-makers, as analysed hereafter.

These problems, among others, represent very difficult challenges for the development of methods to cope with droughts and to mitigate their impacts. These challenges correspond to the multiple facets of the drought phenomena.

- because they are unpredictable or difficult to predict, preparedness measures are paramount in any attempts to cope with droughts;
- as droughts have pervasive long term effects and their severity may be very high, appropriate reactive measures are required;
- the break in the natural water supply usually requires changes in water allocation and delivery policies, as well as in the day-to-day management of water supply and irrigation systems;
- water supplies may be supplemented using non conventional sources, including waste

and low quality waters, thus requiring the enforcement of appropriate policies to control the respective impacts;

- diminished water supply during droughts requires that farmers and other users be capable of adopting reduced demand and efficient water use practices;
- incomes of farmers and other water users may be drastically reduced, so financial support measures are also required to complement reactive measures;
- among preparedness and reactive measures, water pricing and penalty policies may contribute to the effectiveness of drought management measures, and
- the awareness of populations of drought water scarcity must be developed to create a world-wide behaviour pattern oriented to reduce water wastage, encourage water savings and favour water conservation practices.

Desertification and water shortage:

Desertification and water shortage are man induced and are associated to problems such as soil erosion, land degradation, mainly through salinisation, over exploitation of soil and water resources, and water quality degradation. As a result there is a need for policies and measures to be oriented to solve the existing problems and to prevent new occurrences of these problems. Therefore, combating desertification and water shortage includes:

- re-establishing the environmental balance in the use of natural resources.
- enforcement of integrated land and water planning and management policies,
- restoring the soil quality, including the adoption of soil and water conservation measures,
- defining new policies for water allocation, favouring reduced demand and water conservation practices,
- controlling ground-water abstractions and developing measures for recharging the aquifers,
- minimising water wastage,
- combating soil and water salinisation,
- controlling water withdrawals,
- adopting policies and practices for water quality management,
- implementing policies of economic incentives to users, including graduated water pricing and penalties for misuse and abuse of natural resources.

2.2.3. Implications of sustainable development

Coping with water scarcity requires that measures and policies of water management be in line with the challenging and widely accepted concept of sustainable development. This usually requires new approaches towards development and water and soil resources management. New perspectives are required for integrated management of the soil and water. This is not only a question of implementing new technologies and management approaches for allocating and controlling the water and land uses. Rather there is the need for also considering the driving forces governing the pressures on the resources themselves, the behaviour of the users, and the diverse human and social objectives. Despite the enormous progress in development of technological and managerial tools, which are

becoming available to improve management, there are still many gaps in knowledge and in development of skills for transferring scientific and technological knowledge into practice.

The concept of sustainable development is supported by a large number of definitions. The WCED (1987) introduced the concept as the "development which meets the needs of the present without compromising the ability of future generations to meet their own needs". A more specific definition: has been adopted by the WCED (1987): "sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations".

This concept of sustainability relates to the human legacies that future generations will receive from the present. The legacy should enhance future prospects and opportunities and not restrict them in any way. As pointed out earlier, this is of great relevance for regions of water scarcity, where the cultural heritage relative to water has been threatened by the adoption of imported technological and management tools.

The FAO (1990) revised concepts proposed by many authors and formulated its own definition focusing on agriculture, forestry and fisheries: "sustainable development is the management and conservation of the natural resource base and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for the present and future generations. Such sustainable development (in the agriculture, forestry and fisheries sectors) conserves land, water, plant and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable and socially acceptable". This definition fully agrees with that of WCED (1987), uses the same conceptual components and introduces the biodiversity implications.

Analysing definitions of sustainable agriculture, the NRC (1991), states that "virtually all of which incorporate the following characteristics: long-term maintenance of natural resources and agricultural productivity, minimal adverse environmental impacts, adequate economic return to farmers, optimal crop production with minimised chemical inputs, satisfaction of human needs for food and income, and provision for the social needs of farm families and communities".

Adopting the concept of sustainability, water management to cope with water scarcity has to:

- be based on the knowledge of processes which can lead to resource degradation and to the conservation of natural resources;
- include resource allocation to non productive uses such as natural ecosystems;
- consider technological development not only for responding to production objectives but to control resource degradation and environmental impacts;
- value the non-productive uses of the land and water;
- prioritise processes which help reverse degradation;
- include institutional solutions which support the enforcement of policies and rules and socially acceptable decisions and measures for land and water management;
- rely on clear objectives focusing not only on the natural resources by themselves and

the economics of the returns from their use, but also embracing human needs and aspirations.

The sustainable development items enumerated early in this chapter were presented on the basis of the issues referred to above. Resource conservation and environmental friendliness are the main sustainability issues in relation to water and soil. Appropriate technologies constitute an essential challenge to achieve policies and practices well adapted for problem solving. The economic viability of measures to be implemented is a necessary condition for their adoption and a reason for provision of financial incentives. The need for appropriate institutional developments is considered as a pre-condition for implementation of innovative practices, whether of a technological, managerial, economic or social nature. Finally, the social acceptability of measures to cope with water scarcity is particularly dependent on the development of awareness, within the local population, of water scarcity problems and the associated issues.

One potentially beneficial approach is to consider the water not only as a natural renewable resource but also as a social, environmental and economic "good". Since scarcity favours assigning a high value to a good, valuing the water only as an economic, marketable good may provide only limited assistance in promoting sustainability. This is because water acts not only as the basis for production, but it also supports other natural resources and plays a major role in cultural and social contexts, particularly when scarcity gives it a special value. A coupled environmental, economic, and social approach is therefore required in valuing water in water scarce environments.

3. Physical characteristics and processes leading to water scarcity

3.1. Introduction

The water availability of a region depends primarily on its climate and then on the topography and geology. Its sufficiency depends on the demand placed upon it.

The climate is largely dependent on the geographical position of the region. The climatic factors connected to the availability of water are the rainfall and its variability of occurrence in time and space, the humidity, the temperature and wind, all of which affect the rate of evaporation and plant transpiration. The topography is important for water availability since it controls the way rainfall is discharged both in terms of quantity as well as rate, the development of lakes, marshlands and provision of opportunity for surface water to infiltrate. Geology affects the topography and controls the availability of suitable underlying rocks that form aquifers to which water can infiltrate and be available for exploitation.

Water availability, sufficiency or scarcity, are relative terms that greatly depend on the demand placed upon the existing water resources.

Unfavourable climatic conditions coupled with unfavourable topography, geology, demand for irrigation or water supplies for concentrated populations in excess of the available supply are processes leading to water scarcity.

In semi-arid, arid and dry sub-humid regions affected by water scarcity, the processes leading to the water scarcity have specific characteristics, quite different from those of humid or temperate areas. It is important to underline these characteristics that act strongly upon the availability of water and its management. Most of these areas that are likely to be affected by water scarcity have similar factors that make up the identity of their ecosystems and particularly the functioning of the water cycle. These common features are to be found in the climate, the rainfall regime, the conditions of surface runoff and soil infiltration, and in the replenishment regime of deep and surface aquifers.

Of equal importance to the above, are also some non-physical processes that may lead to water scarcity such as population growth, mismanagement of resources and climate change. As discussed in Chapter 2, man induced water scarcity manifests itself as water

shortages and desertification.

Population growth is normally associated with the development of metropolitan areas that provide increased opportunities for employment, and with tourist areas, which especially develop at the seacoasts. Population growth exerts considerable stress on the available water resources and on the water infrastructure, which normally does not keep pace with the demands made on the water resources. As a result the water scarcity problems are accentuated and coping with them becomes even more pressing and difficult.

Quite often water scarcity is exacerbated as a result of mismanagement of the available limited water resources. Careful, prudent and imaginative management is especially called for in areas of limited water resources to enable the demand to be met in the best possible way.

The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". The UNFCCC uses the term Climate Change to mean only those changes that are brought about by human activities. Climate change, which may result from an increase of temperature due to changes in the atmosphere caused by human activities, affects the water availability and the demand for water. The drier the climate, the more sensitive is the local hydrology. These relatively small changes in temperature and precipitation may cause relatively large changes in runoff. Arid and semi-arid regions are particularly sensitive to changes that are likely to reduce rainfall, increase temperature and the evaporative demand of the atmosphere. Drought frequency in some areas is likely to increase the effects of such change. Climate change models (CCM) suggest with medium confidence that the frequency and severity of droughts in some areas could increase, together with the frequency of dry spells and the evaporative demand (USNACC, 2000). However, the uncertainties of model predictions are high and are greatly affected by the environmental conditions under which the temperature observations were obtained. A recent study for California shows that trends in temperature increase are not universal. Observations from rural areas only, suggest that temperature rise may only be occurring in urban areas (Kite, 2001). Despite uncertainties, it is very likely that climate change will produce an increase in demand for water for agricultural production and cause disturbances in the demand for water for natural ecosystems. These disturbances will affect the vulnerability of those natural systems, and produce imbalances in supply, mainly in water scarce regions (Kaiser and Drennen, 1993; Rosenzweig and Hillel, 1998).

Another process that affects water scarcity is the misuse and abuse of land and water resources which leads to desertification. As analysed in Chapter 2, imbalances in water availability are associated with the degradation of land resources in arid, semi-arid, and dry sub-humid areas. Desertification is caused primarily by human activities and is influenced by climatic variations. Desertification reduces the land's resilience to natural climate variability. Soil, vegetation, freshwater supplies, and other dry-land resources tend to be resilient, so they can eventually recover from climatic disturbances, such as drought, and from non-severe human-induced impacts, such as overgrazing. When land is degraded, however, this resilience is greatly weakened. This has both physical and socio-economic consequences.

Some of the physical characteristics of the processes which cause scarcity of water are briefly discussed in the following sections.

3.2. Climatic conditions

3.2.1. General aspects

The climatic conditions commonly present in regions of water scarcity are associated with low and irregular rainfall, high temperature and high evaporation. It is also common that meteorological and rainfall measurement systems are rarely well developed in areas affected by water scarcity. At best, in these arid areas the main climatic parameters are monitored at synoptic stations which have a very low spatial density. Poor levels of observation worsens the problem since it leads to inadequate management of the mediocre quantities of water available.

Figure 3.1 presents the delimitation of arid and semi-arid regions of the world as defined by the Map of the World Distribution of Arid Zones (UNESCO, 1979). This delineation is primarily based on a bio-climatic aridity index, the P/ETP ratio (where P is the mean value of annual precipitation, and ETP is the mean annual potential evapotranspiration). The three zones are the "hyper-arid" zone (P/ETP <0.03), the "arid" zone (0.03<P/ETP<0.20) and the "semi-arid" zone (0.20<P/ETP<0.50). In addition to these criteria, temperature is taken into account based on the mean temperature of the coldest and the hottest month of the year. Consideration is also given to the rainfall regimes (dry summers, dry winters) and to the position of the rainfall period in relation to seasonal temperatures.

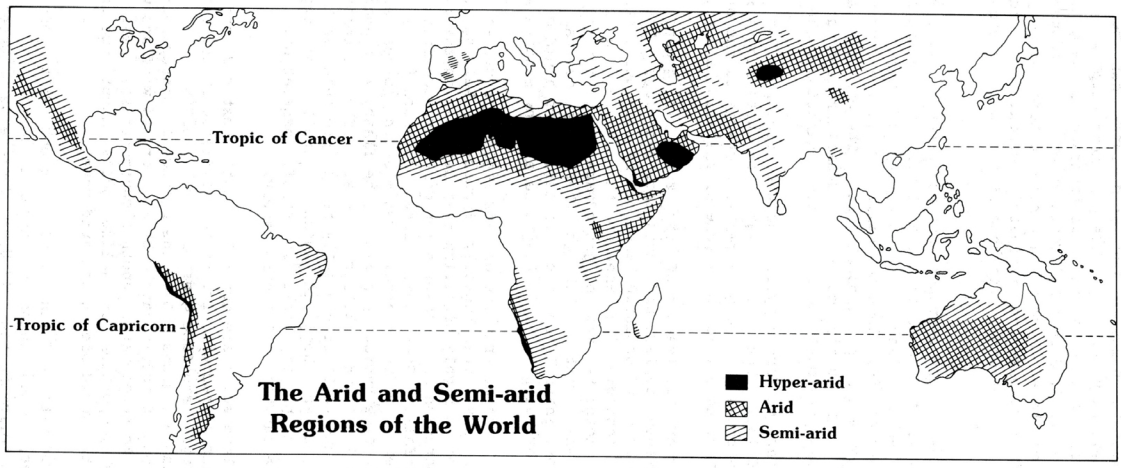

Fig. 3.1. The arid and semi-arid regions of the world (Hufschmidt and Kindler, 1991).

3.2.2. Rainfall variability in time and space

Rainfall quantities and the pattern of their occurrence vary considerably in different climate regimes. In general the lower the annual rainfall amounts the greater their variability from one year to the next. In semi-arid and arid regions the rainfall is irregular and unreliable. In these regions, the rainfall variability and spatio-temporal differences are very pronounced.

Many hydrological and hydrometeorological studies give evidence of such behaviour (e.g. Jones *et al.*, 1981; Demissie and Stout, 1988; Kalma and Franks, 2000). Most of the world's arid and semi-arid regions have climatic regimes in which precipitation is characterized by some or all of the following (WMO, 1996):

- one, rarely two, short rainy season, followed by long and often hot dry periods,
- short rainy periods, rarely more than two days, unevenly scattered throughout the season,
- violent showers, having high rainfall intensity and large spatial variability over a small area, even at a scale of ten square kilometres,
- irregular inter-annual rainfall depths and great local differences that often render the usual statistical tools in climatology ill-adapted, e.g. dissymmetric or multi-modal frequency/probability histograms.

Lack of rainfall has varying significance in the different climatic regimes in the world. In some of the arid zones, there may be several years in which no measurable precipitation occurs and the flora and fauna are adapted to these normal desiccating conditions. In other arid areas, where very little rainfall occurs, the deficiency of the rainfall below the normal results in serious water shortages requiring a number of measures to be taken.

Low annual amounts of rainfall in a region may result from its geographical location relative to the general circulation of the atmosphere, its location on the lee-side of a mountain range, or absence of a topographic high that would favour the formation of precipitation from clouds passing over it. This has a bearing on the surface runoff that is generated, and on the quantities of water that may be recharging the ground water systems. At the same time, the occurrence of rainfall in short and infrequent outbursts creates flash floods, which do not provide sufficient opportunity for water to infiltrate to ground water systems.

It is important to have good rainfall measurements for a sufficiently long duration and of adequate spatial distribution for the appropriate assessment, planning and management of the water resources at a regional level. The need for observed rainfall time-series, both for analysis of water availability and forecasts in the long and medium term, is the requirement most often expressed by development planners and decision-makers. This requirement is currently not usually satisfied in regions suffering from water scarcity. It is therefore necessary to strengthen observation networks for planning and operational purposes and to allow research on rainfall variability and spatial differences (WMO, 1996).

The rainfall measurement in a given location provides point information usually only valid for the area attributed to that rain gauge. A large number of such observation points would be needed for arid and semi-arid regions to provide meaningful information due to the exhibited peculiarities of spatial variation of rainfall in these areas. The knowledge of climate and precipitation is inevitably based on the development and maintenance of such an observing network system in the long term (WMO, 1988 and 2000).

A drought is usually considered to be a period in which the rainfall consistently falls short of the climatically expected amount, such that the natural vegetation is affected, and availability of water for other uses is severely limited. A drought in low rainfall regions could be devastating and disastrous since the already limited existing quantities of water in

such an area could not suffice to cope with the situation. Thus drought has widely different connotations according to location and likely consequences as outlined in Section 3.5.

The intervening periods between rainfall events - dry spells – in regions where aridity prevails are normally quite long and, with the usually high existing potential evaporation, create soil moisture deficiencies, which have to be recovered before runoff will be initiated or there will be infiltration to the aquifers. Thus, in these areas, the effect of a rainfall event on runoff generation and aquifer recharge is reduced compared to the effects of similar events in temperate regions, where rainfall occurs more regularly.

3.2.3. Evaporation

Evaporation and evapotranspiration are important in assessing water availability and they must be considered in water resource planning and management. Water evaporates from soil water and groundwater, vegetation canopies, natural and man made lakes and ponds, streams, and canals and wet surfaces. Evaporation and evapotranspiration are the object of many papers and books, mainly relative to observation and computational procedures (e.g. Burman and Pochop, 1994; Allen *et al*., 1996, 1998; Liu and Kotoda, 1998), including the use of satellite information (e.g. Michael and Bastiaansen, 2000). The discussion here focuses on the particular aspects of evaporation that are of vital concern in arid and drought prone regions and that affect water availability and demand in these regions.

Evaporation affects the quantity of effective rainfall, the yield of river basins, the storage in surface reservoirs, the yield of aquifers and, especially the consumptive use of water by crops and natural vegetation.

Some of the more important factors affecting evaporation are:

- Solar radiation, being the main source of energy affecting evaporation. Solar radiation varies with latitude and season, being generally higher for low latitudes, where its seasonal variation is smaller than at higher latitudes. The net available radiation also depends on the reflectivity of the surface (albedo), the rate of long wave radiation from the earth's surface and the transmission characteristics of the atmosphere.
- Temperature of both the air and the evaporative surface, which is also dependent on the major energy source, the solar radiation. As a consequence of the energy balance, the surface temperature increases when more solar energy is available and a larger fraction of that energy becomes sensible heat. Conversion of energy to sensible heat is enhanced when only a small fraction of the available energy is used for evaporation. The surface temperature decreases when the evaporation rate increases and higher surface temperature occurs when the evaporative surfaces become dry.
- Vapour pressure deficit (VPD) of the air, which corresponds to the amount of water vapour that can be absorbed by the air before it becomes saturated, has a large controlling effect on the evaporation. More evaporation can be expected in inland areas where the air tends to be drier, than in coastal regions where the air is damp due to the proximity to the sea.
- Wind speed above the evaporating surface. Wind represents a major driving force to replace the air layer adjacent to the surface which has been wetted by the evaporated water vapour, with dry air having a higher VPD. As water evaporates, the air above the evaporating surface gradually becomes more humid until it becomes saturated and

can hold no more vapour. If the wet air above the evaporating surface is replaced with drier air the evaporation may proceed. Evaporation is greater in exposed areas that enjoy plenty of air movement than in sheltered localities where air tends to stagnate.

Other factors have a generally broader scale influence on evaporation. The prevailing weather pattern, referring to the atmospheric pressure, affects evaporation. The edge of an anticyclone provides ideal conditions for evaporation mainly when some air movement is operating in conjunction with the high air pressure. Low atmospheric pressure is usually associated with damp unsettled weather in which the air is already well charged with water vapour and conditions are not conductive to enhance evaporation. The nature of the evaporating surface, which may modify the wind pattern, may also influence evaporation. Over a rough irregular surface, friction reduces wind speed, but has a tendency to cause turbulence so that, with an induced vertical component in the wind, evaporation may be enhanced. This influence is often associated with the effects of topography on the nature of evaporative surfaces, the energy balance and the weather variables that determine evaporation.

Evaporation is necessarily dependent on the water availability at the evaporating surface. Evapotranspiration from natural or agricultural vegetation depends upon the availability of water in the soil and the capability of plants to extract this water, which may be retained at high soil water tension. Thus, evapotranspiration is controlled by soil moisture content and the capacity of the plants to transpire, which is conditioned by the climatic demand of the atmosphere. A large amount of the water that is precipitated in a region is returned to the atmosphere as vapour through evaporation from wet surfaces and through transpiration from the vegetation. The water scarcity experienced in regions with low rainfall and long summer dry-spells is exacerbated by high evaporation and transpiration demand.

Evaporation is difficult to control. Development of ground water reservoirs and artificial ground water recharge can reduce evaporation losses. At the same time, proper design of dams located in topography that would store water with minimal free surface area would be advisable. However, such favorable locations are few. In arid zones, not only are evaporation losses important themselves, but high evaporation tends to encourage salinity problems. In such regions, water and soil salinity tend to be high due to the concentration of salts in the soil and aquifers following continuous high rates of evaporation. The resulting saline marshlands, salt-lakes, sabkhas, saline soils and brackish and saline waters, add to the problems of regions with water scarcity conditions.

3.3. Hydrologic characteristics

3.3.1. Runoff regime

The topography, the vegetation cover, the soils and the geology of an area, together with the climatic factors, affect the hydrologic characteristics of that region. These factors control the rainfall-runoff relations as well as the groundwater recharge and storage, so affecting the general water availability in the region. Rainfall-runoff relationships and runoff regimes are dealt with in a large number of Hydrology books and papers. However,

relatively few concern arid and dry environments (Demissie and Stout, 1988; Rodier, 1993 and 1994; NWRC, 2000). The subject is discussed in this Section aiming at providing an overall view of the main problems encountered in water scarce regions.

Stream-flow is the sum of surface runoff, subsurface flow, and ground water flow that reaches the streams. Runoff consists of the quantity of rainfall water left after interception by vegetation, surface water retention and infiltration. The flow regime of a river is the direct consequence of the climatic factors influencing the catchment stream flow, and can be estimated from knowledge of the climate of a region.

The generation of runoff, among other factors, depends on the initial soil moisture conditions in the catchment, i.e. the soil moisture deficit, which represents the difference between the soil water content at saturation and that when rainfall occurs. Dry spells in arid areas are quite frequent and extensive and the soil moisture decreases approximately logarithmically during these periods of no rain. The soil is often dry when rain starts. A crust can form on the dry soil and subsequently infiltration tends to be small, favouring runoff formation and low refilling of the root zone and reduced groundwater recharge. Flash floods are then generated and vegetation growth is not encouraged. Most watercourses contain water only briefly and are known by their Arab designation as "wadis".

Interception, the amount of water that can be caught on vegetation and returned as vapour to the atmosphere, is generally small in arid zones. This is because the vegetation cover is sparse compared to that of temperate humid climates and because rainfall in arid regions is usually of high intensity and short duration. Small interception favours rapid runoff formation, which is typical of flash floods. This ephemeral and sudden runoff regime makes capture and use of surface waters more difficult and produces particularly vulnerable riparian ecosystems.

In most arid and semi-arid climate areas the spatial cover of rainfall events is variable, resulting in contributions of runoff only from part of a catchment. Thunderstorms, which are common in these regions, typically have these high intensities and spatial variability. The infiltration capacity of the soils, which are mostly unprotected by the sparse vegetation, is exceeded quite easily and the excess rain is then available to flow as surface runoff.

The river flows are determined by the local runoff conditions which are essentially controlled by the soil cover and land use, the geology and state of the land surfaces, the topography and physiography of the basin, and by the time and space variability of the rainfall. More generally:

- The streamflow is basically constituted of surface runoff. Base flow generally occurs only in large drainage basins. The complete depletion of flows in dry seasons is the general rule, even in very large basins, in arid and semi-arid regions. In arid areas streamflow usually persist only for a few days after the rainstorm.
- Flows in semi-arid and arid areas are rapid and often violent.
- Erosion and solid matter transport are always important in small drainage basins because of the aggressiveness of rains and the fragility of the soils which are poorly protected by vegetation.
- The time variability of streamflow, at all time scales, is more important from a water

resources point of view than the irregularity of the rainfall.

The irregularity of runoff and the low flows that are often experienced require careful analysis before attempts are made to utilize the water for development. Long-term data are required for any meaningful analysis of the flow regime in areas of such high variability of flow.

The hydrological regime of large rivers in arid zones is seldom well known. On many occasions it is assumed that preliminary studies for the building of large dams can provide such evaluations. This has led to failures and mismanagement of water resources. Matters are worse in the case of smaller catchments. The sustained water availability and the effects of long periods of drought cannot be assessed on the basis of short-term measurements or on the basis of only a few measuring points.

The evaluation of surface water resources can be divided into 1) the measurement of flows in the drainage network, 2) knowledge of the hydrological regime of large basins and 3) the measurement and estimation of flows on small areas that can provide runoff to the main stream. In effect the study should encompass the whole hydrological balance, i.e. partitioning the rainwater among the different components of the water balance (runoff, subsurface and base-flow, soil water storage, evaporation and evapotranspiration, groundwater recharge), and considering the expected modification of the water quality, according to processes likely to be dominant in the catchment hydro-system. Studies of the water balance at different time and spatial scales are essential to allow understanding of schemes which are aimed at gaining control of the usable water in small or large catchments.

3.3.2. Groundwater

3.3.2.1. Infiltration and soil water

In regions of low and occasional rainfall, infiltration is relatively low since the soil has to become saturated before allowing deeper penetration of water. After large rainfall events, the drainage of water from the saturated upper layers of soil occurs by gravity. Drainage of the excess water continues until only the water retained by soil particles in the capillary pores and inside soil aggregates remains. This is water held in the so called “soil matrix”. The amount of water retained in the soil after free drainage corresponds to the soil water content at field capacity. If there is no rain to saturate the soil again, the soil water is gradually depleted by the vegetation and by evaporation through the soil surface. A soil water deficit is created again, which corresponds to the amount of water required to restore the soil to field capacity.

When the water content of a soil is below field capacity and surplus rainfall collects on the surface, the water penetrates the soil at a rate depending on the existing soil moisture content, the soil characteristics, and other factors such as salinity, surface conditions and soil cover. As the rainfall supply continues, the rate of infiltration decreases as the soil becomes wetter and less able to take up water.

Infiltration from rainfall into the soil depends on a large number of factors such as the initial soil water content, the intensity of rainfall and the textural and structural

characteristics of the soil. Soil surface conditions change with time after rain starts because of the impact of raindrops. These may re-locate soil particles and cause a destruction of soil aggregates, depending on the energy of the rain drops, the intensity of the precipitation, the nature of colloids assuring the liaison between soil particles, the percentage and type of clay minerals, and the organic matter in the soil. The cover of the soil surface by vegetation, mulches or litter protect the soil from erosion and are highly favourable for maintaining high infiltration rates. The nature and degree of coverage by vegetation and the dispersive characteristics of the soil surface materials also affect infiltration. When the soil aggregates are not stable, the soil is uncovered, the raindrops are large and the rainfall intensity is high, the aggregates tend to be destroyed, the soil particles become dispersed, the soil pores are breached and an extensive soil crust is formed. This results in a sharp decrease in infiltration rates. When the same soil is well protected by dense vegetation, litter or mulch, the macropores remain open at the surface and water penetrates into the soil at much higher rates.

The unsaturated soil zone may have the capacity to store a large amount of the rain. Unless the soil reaches a high degree of saturation, the water will just be held there until it is evaporated directly or extracted by vegetation. Rain falling on gravelly and sandy soils will rapidly infiltrate and even heavy rains may not generate runoff. On the other hand clayey soils will resist infiltration and even very light rains will result in the generation of runoff.

The cycle of water in the soil, where infiltration into the vadose zone is followed by subsequent evaporation, favours development of hardpans by the deposition of salts and calcium carbonate brought to upper levels by the upward fluxes of water due to high surface evaporative demand. These hardpans impede infiltration, acting as hydraulic barriers even if the underlying ground has sufficient storage capacity for more infiltration. This is quite common in arid and semi-arid regions. Hardpans can also be formed due to tillage in agricultural soils, the so- called plow-pans.

The flashy nature of runoff, as discussed earlier, restricts infiltration since there is not enough time for water penetration. Furthermore, the shortness and irregularity of rainy periods allows only scanty and occasional deep infiltration. In areas with water scarcity, the study of moisture content of soils generally indicates very low variation in the water stored in the unsaturated zone when a yearly time scale is adopted. Temporary storage during the rainy periods rarely exceeds the depth of the plant roots, and as a result deep drainage to the groundwater is quite meager. Such conditions are conducive to a strong and rapid return of water to the atmosphere by evapotranspiration.

3.3.2.2. Recharge of groundwater

In regions with annual rainfall less than 250 mm, the recharge of aquifers is very small for all except the most permeable soils. The amount of recharge depends on the permeability and retention capacity of the soil, and the distribution of rainfall in relation to the evaporative demand. A more detailed analysis of groundwater exploitation and recharge is presented in Chapter 6.

The retention capacity of the soil controls the quantity of soil water that is held in storage. This quantity of water is depleted during dry periods, and the difference between it

and that needed to saturate the soil is the amount of rainfall required to satisfy the soil-moisture deficiency before recharge can take place. If rain occurs in a number of events during the wet season and dry weather intervenes between them, then a substantial part of the total rainfall would be used to refill the depleted soil moisture storage, so leaving only a very small quantity, if any, for ground water recharge. This generally, is not the case for sands and sand dunes and alluvial stream channels which have a low specific retention of less than 5 percent. These allow penetration of rain deep enough and beyond the zone of seasonal drying so that it becomes recharge to the aquifer.

The channel beds are normally the areas through which most of the recharge takes place. Recharge also occurs in flood plains at zones where there is pronounced presence of coarse alluvial sediments, at zones where the outcrop is weathered, and at fractured exposures of bedrock. Runoff in arid regions is often heavily laden with sediments. If the water is not too turbid and if the channel bottom is permeable enough, water will flow into the gravel and sand of the channel bottom. Part of this water will return to the atmosphere by evaporation and part will go into recharge of the underlying aquifer. Most of the recharge tends to take place at points where the channel is constricted rather than where the flow spreads out over a large area. This is because at narrow points of the channel the sediments are more permeable, being of larger size due to the velocity potential of flow.

In arid regions the usually great depth to the water table in the upland areas and the very small hydraulic gradient suggest there will be only relatively small amounts of recharge in these regions.

3.3.2.3. Groundwater

Most of the distinctive hydrogeologic features of arid regions are related to the quantity and quality of available ground water. In dry regions, groundwater is a very important source of freshwater for domestic, agricultural, and industrial use, and it may be the only source of water supply over large parts of the year.

Groundwater resources play a significant role in the hydrologic cycle and the water balance of a region since they act as a buffer, providing significant amounts of water during years of low precipitation or storing a significant part of runoff on the occasion of high precipitation. In view of meagre recharge in areas of low rainfall, aquifers are destined for ultimate depletion unless prudent and very conservative development is carried out. Such development should not seek to extract more than the long-term amounts of recharge.

Due to the great quest for more water in these regions, aquifers are in many cases overexploited, and suffer much degradation, such as lowering of the water level, salinisation and intrusion of marine water, and mineral and organic pollution. This unbalanced situation is typical of man induced water shortage and desertification. The very strong demand exerted on the most easily accessible aquifers brings about salt accretion to groundwater that becomes a serious problem near the coast or in the vicinity of aquifers with low quality water. This is more pronounced in areas of increasing water scarcity where water from different aquifers of varying quality is imported and blended with surface waters to maintain existing land uses and to meet other demands.

The exploitation of aquifers in regions of low natural recharge and scarce surface water is to a large extent controlled by the low rainfall and the relatively small amounts of

runoff, which is often associated with high erosion when the vegetative cover is poor and flash floods are the rule.

Extensive aquifers found in arid regions are often the result of past climates which were considerably more moist than the present conditions. Other aquifers at the fringe of high mountain ranges may owe their replenishment to higher rainfall in the uplands.

Closed basins filled with fine sediments of recent origin, are often highly saline especially in areas where water remains at the surface for some time before it evaporates. Aquifers with good quality water are only found along the margins of such basins or in deeper aquifers not affected by present arid conditions. The most significant aquifers are formed by river deposits that are usually a mixture of poorly sorted, and of generally low permeability, sediments. The most permeable zones are found only where the runoff persists long enough to sort out and deposit only the coarser material in the streambed. These conditions can normally be expected only in former narrow valleys and channels and they are normally of limited extent.

Furthermore, due to the high erosion experienced in arid regions the thickness of alluvial material is limited and the bedrock in many cases is exposed or quite near to the surface. On the other hand, widespread consolidated and semi-consolidated aquifers are sometimes found in regions of water scarcity with considerable quantities of ground water in storage which was recharged in past geologic times under different climatic conditions. The mining of these aquifers also entails increasingly heavy constraints, even if the estimated storage is huge compared with the annual consumption. Their development and use must be based on sound hydrologic studies since overexploitation will inevitably result in their depletion and extinction.

3.3.3. Sediments

In arid and semi-arid regions, several environmental conditions favour water and wind erosion. On the one hand, soil erodibility tends to be high because lack of organic matter and the presence of salinity lead to low stability of the soil aggregates. On the other hand, rainfall and wind erosion are quite strong. Rainfall events are often very intense and wind storms also have a high potential to detach the soil particles and transport them large distances. Erosion is aggravated by the reduced protection offered by vegetation, which is mostly sparse and offers little soil coverage, and by the lack or insufficiency of conservation measures in agricultural lands. Then, detached soil, of silt and clay size particles, is easily transported by overland runoff to the ephemeral streams, thus providing a ready supply of sediments to the streamflow.

In low rainfall regions, runoff can be generated from even small rainfall events falling on rock outcrops without vegetation or on hard clay surfaces. However, only in the very low intensity rain events is the runoff likely to be free of suspended sediments. More commonly, in low rainfall regions, depending on the soil types, the relative lack of vegetation and the sudden bursts of short but intensive storms cause the runoff to erode large amounts of soil resulting in mudflows and highly turbid water.

In addition to the intensity and conditions of a rain event, the amount of erosion depends considerably on the type and state of the land surface. The extent of plant cover, roughness and micro-relief of the surface, porosity, texture, structure, and salinity of the

soil and the soil moisture content are some of the basic controlling factors. In low rainfall areas, the lack of vegetative cover, the moisture deficiency and surface crusting are critical. Problems are worse when the topography comprises steep, long slopes, and the lithologic features encourage sheet erosion and the transport of detached particles by overland flow. Gullies are very often formed under these conditions. Therefore, in water scarce areas, surface flows are very often associated with large sediment charges, and the deposition of fine sediments in flat areas and stream beds make the infiltration, that would provide for groundwater recharge, more difficult.

Erosion and salinity are among the main problems affecting soils in water scarce regions. This physical degradation, together with the soil moisture stress and loss of fertility associated with the soil losses, is among the most important causes of desertification. Other causes are the unbalanced land and water uses, which are very often much above the potential capability of those natural resources. When too much pressure is placed on their exploitation, their resilience is not sufficient for recovery and unbalances become evident and, in many cases, quite permanent.

3.3.4. Water quality

In temperate zones the blending of large quantities of surface runoff tends to maintain reasonable water quality standards. These large quantities of water are absent from arid and semi-arid climates. The result is that the reduced flows are laden with increased amounts of salts leached from the soil profiles and the groundwater, which is then enhanced by the very high evaporation. Furthermore, fertilizers and pesticides from agricultural activities that find their way to the groundwater and streamflow appear in increased concentrations in those water bodies due to the low recharge and the low discharges in the streams. Effluents from urban and industrial areas significantly add to the problem, mainly affecting the quality of streamflows. The fact that floods are sudden and are highly charged with sediments worsens the water quality problems.

The harsh evaporative environment in areas of low rainfall adds to the amount of salts present in surface waters. The high temperature and the addition of salts and nutrients to surface water bodies easily create conditions of eutrophication, which largely affect water quality and the riparian ecosystems.

Groundwater quality in regions of water scarcity is often very low. The contribution of ground water to surface runoff often increases the salts present in the surface flows.

Water quality degradation, which affects both surface- and groundwater, often results from man made water shortages and is a cause of desertification. When high quality water becomes contaminated with salts, charged with untreated municipal and industrial effluents containing toxic substances and heavy metals, that water becomes unavailable and there is pressure to explore and exploit other sources of water. Consequently, water becomes scarce or the degree of water scarcity is increased. If the degradation of water quality can be reversed after appropriate management, which is more likely to be possible with surface water, the water shortage problem may be overcome. If reversal of that degradation requires long term measures, such as are more likely for groundwater, then a desertification process may have been installed. Recovering the quality of groundwaters to an exploitable condition in areas of very limited recharge and high demand pressure may be a task for

several generations or may be impossible. Considerable attention must therefore be placed on avoidance of man-induced water scarcity, which can mainly be combated through protection, preservation and good management of the resources.

3.4. Drought and water scarcity

3.4.1. Definitions

As noted in chapter 2, drought is considered to be a temporary natural condition. It is not a term necessarily related to arid conditions. Nor should it be used to describe the normal year-to-year dry season, which is part of the climatic regime. Rather drought is defined as below average, or less than usual availability of water. The term is rarely applied to short periods, say of weeks or one or two months duration. The term drought is usually applied, as in this book, to periods of several months, up to much longer periods. However where much longer periods of below average water availability occur it is possible that such an event is indicative of climate change.

Drought is usually considered to be part of the normal variability of the local climate. Drier than usual periods must be expected as part of the normal sequence of events. However if a drier than usual period continues for many years it is unlikely this is part of the normal continuum of events. For example in the Sahel the observed rainfall in the early 1960s was well below average (Nicholson, 1993). When these below average rainfall conditions continued for over 30 years it appeared that a climate change had occurred. Only in the 1990s has the rainfall been similar to that which was observed in the first half of the 20^{th} century. Does the return to higher rainfalls suggest the 30 years or so of low rainfalls were indicative of a long period of persistently below average rains which are part of the normal variability? No categorical answer can be given at this time. It is known that long-term persistence occurs in rainfall and streamflow data but this is the longest significant deviation from usual conditions that has been properly documented. Long periods of above or below average rainfall conditions occur in ancient literature and oral history but this appears to be the longest period of an actually recorded local extreme. Similarly the south west of Australia has experienced a 30% reduction in annual rainfall for the last 20 years (Nicholls and Lavery, 1992). Climate change as usually defined would be expected to produce such changes but are these observations indicative of very long term persistence, and therefore drought, or of climate change, with the new climate regime being indicated by the recent observations?

3.4.2. Manifestations of drought

As several authors have suggested (Heathcote, 1969; Jackson, 1981; Cordery and Curtis, 1985) various sectors of the population define drought differently - as has already been noted in chapter 2 - and so some care is needed to explain what is meant. For example, below average rainfall may be considered to constitute drought. However if the below average conditions occur when there is usually little or no streamflow the water resources may not be affected. Alternatively it is possible that the (small) rain that does fall may occur just at the right time to sustain crop growth, with no apparent drought for agriculture. Similarly water resources drought, i.e. sustained below average river flow or below average

recharge of aquifers, can occur when rainfall is average or above average. If the rain occurs as a series of very small but frequent events, there may be no surplus of water over what is needed to supply the root zone of the vegetation, but the total rain may be quite large. In Colorado in 1977 there was a serious drought which led to restrictions of supply in the city of Denver, and no water in the irrigation supply reservoirs to the north of Denver. However the corn crop that year, even from the irrigation farms, to which no water was delivered from the reservoirs, was the largest ever. Rain occurred during the corn-growing season at just the right timing to provide optimum crop development, but was insufficient to cause runoff into any of the local reservoirs. Hence there is probably a need to distinguish between "meteorological drought", "agricultural drought", "water resources drought" and perhaps "economic drought" in which the water resources are insufficient to sustain local industries and income producing recreational activities.

3.4.3. Forecasting drought

Around the world there has been considerable effort to develop practical methods of forecasting precipitation some months or even years ahead. It is clear that if reliable forecasts could be made there would be opportunities for development of strategies to reduce the devastating effects of drought. For example if a drought is about to begin crops demanding less water could be sown, and water supplies could be managed to conserve supplies before the drought starts, to ensure vital life-support-supplies could be sustained through the drought.

Some successes have been achieved with forecasting (Hastenrath and Greischar, 1993) in limited areas. In many other parts of the world very promising results (McCabe and Legates, 1995; Cordery and McCall, 2000) have been achieved which suggest it should soon be possible to forecast drought up to 2 years ahead. The basis of these promising developments has been the demonstration of widespread influence on local precipitation of global ocean surface temperatures and large scale variations of these within the major oceans (e.g. the El-Nino Southern Oscillation in the tropical Pacific Ocean and the North Atlantic Oscillation in mid latitudes).

3.5. Meteorological and hydrological data collection and handling

The meteorological and hydrological data in an area must be sufficient, reliable and accessible to be of maximum use and benefit for the community. The hydrological systems are not understood well enough for reliable theoretical models of local conditions to be developed. In order to carry out water resources planning and design it is vital that some local data be available. For maximum usefulness there needs to be a combination of field data measurements and storage and retrieval systems together with the application of advanced processing techniques. Data acquisition and their management should be planned in such a way as to suit the local conditions, the available staff and the financial capability. This could be developed gradually and prioritized so as to solve the most immediate problems.

Quality control and well-developed operating systems, including field check observations, should form components of the primary data-processing system. These

primary data should be purpose oriented and follow a plan for meeting defined objectives. Among others, one may distinguish objectives of different types: meteorological, in relation to the synoptic weather stations; hydrological and water resources planning and management, relative to hydrological and water quality monitoring; agricultural, concerning agrometeorological networks for provision of irrigation advice and pest and disease information; drought management, referring to drought watch systems.

Data processing includes checking for completeness, long-term consistency, stationarity of the measured variables and statistical analysis of the data (Haan, 1977; Conover, 1980; Kottegoda, 1980; Helsel and Hirsch, 1992). The latter includes fitting of frequency distributions to the data and using the data in parametric models and multivariate time-series analysis. The validity of derived relationships should be tested on independent data. The degree of both detail and precision of the analysis should be consistent with the quality and sampling frequency of the available data and with the accuracy required by the application of the analysis. Using good data is always more important than using abundant data.

Time-series play a crucial role in water resources evaluations. Stochastic time series models are fitted to the corresponding input variables such as river flows, rainfall, evapotranspiration, and temperature. These models in turn can be used for the simulation of the operation of the system. Mean values and variances often give a good characterization of the phenomena under study; however, these values do not reflect the internal properties of the investigated time series and further statistical analysis is required.

The homogeneity of hydrological data is an important requirement for a valid statistical application. A detailed analysis of the data is the most effective method of evaluating data homogeneity. The methods of analysis are usually based on plotting different types of variables against time or data collected in other locations in the same environmental area, or by relating them to other variables to discover causes of a disturbance of homogeneity. Anthropogenic disturbances and changes of climate can only be detected using high quality data (e.g. Refsgaard *et al.*, 1989).

The WMO Guide to Hydrological Practices (WMO, 1994) and numerous other textbooks and reports (e.g. UNESCO, 1982 and 1987) provide methods and techniques for processing and numerous tests for examining the normality and homogeneity of hydrological data. The integrity and quality of data cannot be over-emphasized and one needs to ensure their quality before applying them for any hydrologic analysis.

Of particular interest are the frequency, severity, duration and spatial extent of droughts that seriously worsen the water scarcity conditions. There are several methods of analysing hydrological and meteorological data for determining drought sequences. WMO (1994) adopted a statistical procedure for analysing low flow time series. Other approaches for analysing streamflow discharges are available (Cancelliere *et al*., 1995). Rainfall data is currently analysed at the local scale through the theory of runs (Guerrero-Salazar and Yevjevich, 1975), the Palmer drought index, PDI (Palmer, 1965), and the standard precipitation index, SPI (McKee *et al*., 1993). Regional droughts are often based on the theory of runs (Santos, 1983; Cancellieri and Rossi, 2002) but a modified SPI may also be successfully utilised (Paulo *et al*., 2002). Drought indices may be used for drought warning and lead time assessment (McKee *et al*., 1995; Lohani and Loganathan, 1997).

The value of data in water resources management, especially under water scarcity conditions is immense. Nonetheless, water resources data collection programs are very vulnerable to cuts in government expenditures since they are not seen to have an immediate impact upon the community. Any adverse effects arising from a curtailment of these programs may not become evident until many years in the future. Because costs of data acquisition and primary analysis are very high, some governments only provide data to potential users for a fee. Then, to save costs, users often restrict to a minimum, often below what may be reasonable, the amount of data they use, so degrading the quality of the outcomes of any studies and projects based on the data. On the other hand, the increasing demand on limited water resources and increasing environmental degradation due to human activities, has ensured that the demand for reliable water resources data is increasing. At the same time it is becoming evident that there is an increasing scrutiny of the reliability of data and that there are expectations from users for higher quality data.

The above clearly point to the need for a well thought out and technologically advanced information system for water resources management (Iacovides, 2001). Such a system would define the type and extent of data required and should be such as to provide all the information necessary for integrated water resources management and for coping with water scarcity. To this end it should include a database system, and use of models and geographic information systems to facilitate decision support systems in water resources management.

4. Conceptual thinking in coping with water scarcity

4.1. Introduction

When thinking of coping with water scarcity there are many issues to be considered other than the direct technical matters dealing with collection of water and prevention of losses. The human dimension is of great importance. Over its history humankind has developed cultural traditions, social structures and institutions which have a huge impact on the availability and use of water. For example in some traditions there is a concept of ownership whereas in others the idea of ownership of a product of a natural process makes no sense.

This chapter attempts to discuss some of these "non technical" issues and their impact on water resources availability. To those from a particular culture, the traditions of another place, and their influence and constraints on water resource use may appear strange and even unacceptable. However in dealing with cultural issues great care is needed, particularly to understand how the current situation developed historically. To advocate change of some practices may be offensive to the local population, no matter what the logic from a water resource point of view. Therefore advocacy of change must be approached with great sensitivity and empathy. It may be that no change will be possible during the life of the current generation. Other traditions however, may have no more basis than "accepted practice" and change of these to increase benefits to all concerned may only be a matter of logical argument and demonstration.

This chapter attempts to consider some of the key ideas that influence water resources development, and therefore also impact strategies for coping with water scarcity.

4.2. Social value of water

4.2.1. Water for life

Water is essential to life and therefore it affects lifestyles. Conversely in areas of water scarcity the availability of water is very much affected by lifestyles of the local population. Land use and animal husbandry practices have considerable influence on water use. In

water scarce regions there is a need to capture some of the precipitation for household use and to retain as much as possible of the remainder in the soil to promote crop or forage growth. Runoff from roofs and surfaces which have been compacted by the passage of many feet (animal and human) can be directed to storage locations. However crop and grazing lands need to be kept tilled, or at least in a non compacted state to promote rapid infiltration of precipitation whenever it occurs, and to retain water in the soil, to avoid soil water evaporation.

4.2.2. Differences between urban and rural needs

In urban areas there is almost always some form of municipal water supply, either in the form of a piped system or using tankers. The major concern of municipal water managers is to capture water, usually outside the urban boundaries, and to store it for later use. Roof water can be used in-house and roofs need to be constructed to facilitate capture of the water. Land surface runoff can be directed to sumps from where it can be extracted for use or encouraged to percolate to an aquifer from which it can later be pumped as needed.

Many of the poorer segments of urban societies need to collect water from a standpipe or from a tanker. In these situations the distance the water must be carried to the point of use (residence) is usually less than 200m.

In rural regions there is usually no piped water supply. There may be tanker delivery of water, or more commonly, each household needs to collect its own water, usually from a communal well or from a stream or lake. Here much more labour is required to obtain water – to lift water from a well or to carry it a considerable distance from the lake. Water collection may consume a significant proportion of the time and physical labour of the household.

Drought periods tend to bring more hardship to rural households than to urban dwellers. Urban supply systems, though usually far from perfect, incorporate opportunities for managers to restrict supply during drought and to conserve at least enough to maintain drinking water supplies during the drought. However in rural areas the lack of a managing authority means it is “everyone for himself” and water tends to continue to be used without restriction. As the drought continues the usual supply source may fail completely. To survive, the population must move near to a water source (perhaps a city) or carry water to their houses from distant sources. For these reasons drought usually has more severe impacts on the rural population than on city dwellers. However in extreme drought, if city supply systems fail completely, the poorer urban dwellers are likely to suffer more than their rural cousins because water will be brought into the city at great expense, because sources are quite remote. The prices demanded for water under these circumstances are likely to be beyond the reach of the poor.

Almost all water-scarce regions of the world have at least brief, infrequent episodes of surface runoff, and systems need to be in place to capture this water when it occurs. The systems must be passive (ie not needing any human operation) and ready for acceptance of water at all times. The random, brief occurrence of precipitation means that human operation is unlikely to occur successfully in every runoff event and so systems needing human operation will only catch part of the possible available water. The quality of captured water may be an issue but quality can usually be improved relatively simply. The

key issue in regions of water scarcity is to maximise the capture and conservation of any available water.

4.2.3. Differences between arid zones and non-arid areas

Arid zones are readily recognised as regions of water scarcity but many non-arid regions also have scarcity of water supply, usually due to seasonality of precipitation, the density of the population and the nature of the accepted water use practices. However in the wetter areas water scarcity can be overcome by changes in water management, for example by encouragement of capture and consumption of roof runoff and re-use of water. In arid zones the scarcity is more likely to be of an absolute kind, with water in all its forms being very limited. Wise management of the scarce resource can significantly improve conditions and lifestyles, but in the arid zone per capita water use will always be lower than it could potentially be in the wetter areas. In the arid zone water has a very high price. In monetary terms the price may not be significant but the collection, storage and supply of water in the arid zone will always require either a high level of technology or collection and transport of water from some remote location.

Most communities have adapted their water collection and use practices to their environmental situation over many years. However recent ideas and simple, inexpensive technologies mean that these time honoured practices could realistically be improved upon in many situations, water availability could be increased and the cost to communities of their water supply could be reduced. Flexible but realistic thinking and willingness to consider new ideas are required.

4.2.4. Social effects of water supply/collection practices

In many areas of water scarcity collection of water consumes a large part of household labour, and therefore of the time of one or more of the household members. While this labour is a major cost to the household, it also provides much opportunity for social interaction for the water collectors. Change, to reduce the labour in water collection, would inevitably change the social structure of a community. This must be recognised as a consequence of change of water management practices. The social change that results may be resisted, resented and may lead to upheaval within a community. It is possible that improvements to water management, which may benefit all, may be opposed by community leadership because they fear social disruption or they do not wish to see the members of the water collection group freed from the constrictions of their water collection activities. Hence any proposals to change water collection or water management needs to be preceded and accompanied by an educational program aimed at preparing all levels of the community for the changes that will occur, highlighting the direct (increased supply at lower cost) and indirect (less labour consumption by water collection) benefits for the whole community. Arid zone communities are often isolated and conservative, resistant to change, particularly when that change may impact on the social structure.

4.3. Environmental value of water

Water is a major factor in shaping the natural environment. The amount of precipitation and

its distribution in time has a major influence on the vegetation of the region. However it also influences the species of fauna to be found in the region and has a large, but long term influence on the shape of the landscape. Any changes in the water regime will inevitably lead to changes in these other components of the local environment. This is particularly true of the effects of water extraction on the flow regimes of rivers. There is continual community debate over the desirability of maintaining "natural" conditions in rivers. However the definition of these natural conditions is very variable and dependent on the social, political as well as scientific agenda of the personnel involved.

It has been clearly shown that change of flow regime, by extraction of water or by impounding water, can have large effects on the whole of the downstream river valley. In most cases the initial effects are small because (1) early in the development the flow regime is only slightly changed, and (2) time is required for the impacts to become apparent. However, as the water resource is developed further, the impacts become greater, usually affecting both surface and groundwater downstream of the point of development.

There are many examples of very large environmental impacts of development of water resources. In general these have not been foreseen, either because at the time of the development there was insufficient scientific understanding of water resources processes, or more recently because the planning was piecemeal, considering only the direct benefits of the development and being unaware of, or ignoring possible detrimental effects downstream. Some of the larger impacts (they could be termed disasters) have been (1) the large reduction of inflows to the Aral Sea, and the lowering of its surface by over 20 m and the reduction of its surface area by more than 50%. Here natural inflows have been diverted to consumptive use by irrigation. (2) In the Mediterranean Sea adjacent to the Nile delta the fish catch has fallen dramatically as a result of trapping of nutrients in the form of suspended solids in the Aswan High Dam. There are numerous writings suggesting that the High Dam has brought benefit to Egypt of increased food production, but has cost the nation dearly in reduction of protein supply (fish), natural supply of agricultural nutrients, and has greatly increased the incidence of serious diseases such as schistosomiasis. (3) In Australia development of water resources from rivers that pass through the arid zone on their way to the ocean has lead to salinisation of the land surface and river waters and has led to devastating blooms of cyanobacters (blue-green algae) which are toxic to mammals.

4.4. Economic value of water

4.4.1. Safe water supply has a cost

Water has great value to all life. However it is often viewed as a naturally occurring commodity which is freely available to all. This sentiment has lead to the view that water should be available free of any charge. This view is reasonable if there is no development of the water resource and individuals collect their own supply. However in the 21st century Earth's population has increased to a point where it is no longer possible, nor desirable, for individuals to collect their own supply from the natural source. Except in areas of very sparse population water supply systems have been developed, which involve some form of collection and delivery. The collection and delivery activities incur costs and so all water

supply systems require funding, both of a capital nature to set up the system initially, but also ongoing funding to meet operational and maintenance costs.

It is probably unfortunate that in many countries the political view has prevailed that the population should not be charged for water supply. As political and economic conditions have changed most of these "free water" schemes have been unsustainable. The result has been that about half the earth's population does not have in-house delivery of safe water. On the other hand electricity is delivered to more than 80% of all households, world-wide. The difference is that everyone accepts that electricity is produced at a cost, and most people are willing to pay for energy provision.

Resolutions to provide running potable water to the majority of households, world-wide, after the Mar del Plata conference in 1978 have failed, primarily because there has been no firm political will to charge realistic prices for the supply of water. Until educational programs can convince the population at large, and the political leaders that sustainability of water supply can only be achieved when users pay realistic prices for the supply, large sectors of earth's population will continue to pay the price of living without a safe, in-house water supply. This price is very high in terms of the labour involved in collecting water each day and in terms of poor health due to use of insanitary water and poor hygiene standards due to insufficient water availability. Experience in regions with safe, in-house water supply shows that the cost to individuals of not having a safe delivery system is far higher than the real cost of construction and operation of an adequate system.

The problem of inferior, inadequate household water supply in most areas of the world is not one of water scarcity but one of political determination to charge a sufficient price for supply to cover the real, total cost of the supply system.

Aid agencies and NGOs have provided less and less funds for development of water supply schemes as they have observed that Governments refuse to charge for water supply at a level that will allow for maintenance of the system plus repayment of the initial capital cost. No matter what the political philosophy of a country, such policies are unsustainable, as evidenced by the supply of electricity to most households, but of water to only a minority of households.

4.4.2. Water pricing

How should the price of water be determined? This is a very difficult question, especially when the supply, in the form of precipitation, is totally free, and many subsistence households have little opportunity to exchange labour or goods for money to pay water charges.

However this argument does not provide a basis for supplying water free of charge. How do households pay for electricity? A large amount of imaginative work is needed to develop charging systems that fit into the local culture and customs. Households which do not have a supply currently pay a large monetary price for deliveries of water by cart, or in terms of labour (by the women and children) to collect and carry the household water. Imaginative programs can be developed to harness these large energy resources to make water supply systems safe and sustainable and much more efficient without creating social problems. Solutions require imagination and political will and leadership.

4.4.3. The water supply market

Water pricing has been discussed above. However it is often suggested that real pricing of water cannot be implemented because the poor could not afford to pay. This is nonsense. The poor pay for electricity. Realistic pricing mechanisms require measurement of water consumption but the excuse is brought out that water meters are too expensive for the poor. However 80% of households worldwide can afford to pay for an electricity meter. Which is more important for life — water or electricity? Tariff structures can easily be developed to ensure the poor can afford the minimum living requirements but that those who use large quantities pay a premium price. There should be no reduction of tariff for large users since one of the aims of pricing is to reduce consumption. However such a tariff structure causes problems for irrigators who are very large consumers. Hence tariffs for irrigation need to be different from those for urban households, but they still need to be economically realistic. That is, all the water supplier's capital and operational costs should be covered, at the very least. If income is too low, the inevitable result will be neglect of maintenance and eventual collapse of the scheme. There are many examples in water resources development history.

A major problem with the idea of a free market for water is that there will always be uses which can afford to pay a high price for water. For example most urban household users would have no difficulty competing for water supply on the basis of price alone. However high prices for irrigation water not only affects the irrigator but eventually affects the urban dweller since the price of food will need to rise or growing of food will cease. The world, and local economies have adapted to low food prices and so radical changes in irrigation water tariffs could disrupt whole economies. Careful, multi-disciplinary thinking is required to develop sustainably structured water tariffs and to integrate these into the broader national and international economic environments.

4.5. Priorities for water allocation

4.5.1. Who owns water?

The major problem of water allocation is in reaching the initial agreement or acceptance of ownership or the right to allocate. There is no universal agreement on the status of water as a commodity. It is similar to the status of land. Can it be owned? Should it be a common trust to be used according to agreements? Who has a right to ownership or to be a party to a use agreement? These are questions which have strong anthropological and cultural links for which solutions (or disputes) have developed through history. Cultural and anthropological understanding has been over-ridden in many instances by water scarcity, because in recent years water use has escalated, driven by increased population, rising standards of living and the economic advantages of water availability.

There is not space here for a broad discussion of cultural traditions of water rights and ownership. However in recent history many of these cultural links have been swept aside by the political and economic philosophies of majority population groups and in most places water resources have become a political issue both within and across political boundaries.

Understanding and development of strategies for coping with water scarcity must take account of this wide range of external forces. Strategies must be developed which are compatible with local political and cultural realities. One particular coping strategy may appear obvious to one cultural group but may be totally unacceptable to another, perhaps for reasons which have their origins in ancient history, but which appear to pragmatists to have no relevance today. In the long term a strategy such as this will not be sustainable. Successful strategies will be those which recognise and either accommodate or over time, by education, change the cultural and political environment.

Our original question was who has the authority to allocate water? In modern sovereign states water is generally accepted as being linked to territory. It is linked to the location on which it settles from the atmosphere. But what of trans-boundary rivers? Does the upstream state have a right to consumptively use all of the water in the river? As technology develops who will have the right to trap water from the atmosphere and prevent its "natural" travel to precipitate on a different sovereign state or on a neighbour's land?

4.5.2. Water ownership

Is water to be shared equally by all, to be owned by the state, or to be used freely by those who care to access it? All these, and many more systems underpin the water law/water allocation systems currently operating in various parts of the world. First in, first served systems may be fine where the resource is much larger than the demands made upon it. However few parts of the world still have this luxury. Similarly a totally unregulated market can only work where it is acceptable for large sections of the population to be denied any water – but genocide is clearly not acceptable. The intermittent and random nature of natural flow of rivers, quite different from the approximately constant rate of consumption demanded for most human activities, means that large scale intervention is required to smooth out the natural fluctuations and make the resource more useable. Large scale projects to provide this constancy of supply usually require state intervention and provide opportunities for states to appropriate ownership to themselves and to enact laws to regulate allocation of water. Ownership of this type usually provides opportunities to raise funds or charge for water. However, as we have seen, some states or regimes have decided for various political and cultural reasons not to charge for allocation or supply of water, but as a result have found it very difficult to provide adequate water supply systems for their citizens.

There can be no ideal ownership system for water. The system adopted must be compatible with and serve the needs of the constitution and population of each locality. The real need is to develop a system that is equitable and is seen by the majority of potential water users to be so.

In areas of water scarcity ownership/allocation systems will always be a focus of attention and potential conflict. Systems that are seen to be fair now rarely contain provision for managing the increased demands of the future (due to population increase and higher lifestyle expectations). Economic development and long term investment require certainty regarding future water supplies, but any system that provides for revision of allocations as population and demand increases introduces enough uncertainty to stifle investment and curtail development.

In all areas of water scarcity there is a need to build institutional frameworks and allocation systems that allow clear statements and guarantees of future (perhaps reduced, but by forecast amounts) supplies so that potential investors can adequately plan and estimate long term returns. Without long term planning and assurances of future water availability development will be stunted.

Therefore it would appear that in regions of water scarcity ownership of water is probably not the key issue. Rather political stability and water institutions which can provide guarantees of future amounts of water to be supplied, and of its price, are probably far more important.

4.5.3. Water for human life

The needs for access to water supplies are obvious but it is worthwhile to summarise them here.

Firstly water is needed for drinking and food preparation. This water needs to be of high quality but the amount needed is not large. Under most conditions a supply of as little as 10 l/person/day would not restrict activities. Secondly water is required for cleaning and basic hygiene. Again the amounts required are not large but tend to increase greatly with general standard of living and inversely with the price of water. The quality requirements of this water, for bathing, cleansing of utensils and living space and for transport of wastes is not high. In modern society very large quantities of water are used as a transport medium for wastes. While this may be an effective means of waste removal it does not make sense for regions of water scarcity. Use of methods of solids removal requiring little or no water should be investigated.

Food production can be the largest user of water. However in regions of water scarcity there is a need to find crops that can survive rain-fed conditions or which need minimal irrigation. For example it makes no sense to grow rice in areas of high water scarcity. However rice is currently grown in some water-scarce countries to obtain foreign exchange and for local political reasons, but the water loss to the atmosphere, rising water table and soil salinisation that results makes no sense at all. Research is needed to investigate the types of food that can be produced with less water. At the same time studies are needed to investigate possible dietary changes towards the low-water requirement food. These investigations need anthropological and cultural input as well as biological and agricultural expertise.

4.5.4. Water for industry

As was stated above it makes little sense to site high water demand industries in areas of water scarcity. However this situation does occur, as a result of historical developments and for cultural reasons. Effort is needed to change this situation, either by moving the industry or by implementing a comprehensive water recycling program to reduce the water consumption. Implementation of recycling schemes is often resisted and strategies involving real supply and demand pricing, environmental restrictions and public education probably need to be used together to achieve change. Most industries can reduce their water use but there is always a cost. However with realistic water pricing it may be cheaper to use less water but at the same time to raise employment. In most parts of the world there is little

real incentive to save water, "it is a free renewable resource". If the real economic value of water was charged, many users, particularly industries, would quickly change their water-use practices.

4.5.5. Irrigation

Irrigation is the human activity which consumes most water. Irrigation water use is primarily for production of raw materials of food and fibre. Irrigation farmers must compete with their fellow irrigators and with dry-land farmers and as a result they can generally only operate where water input costs are low. In general, irrigation water is not treated in any way so the costs are those of collection and application of the water plus taxes. In some countries government tax raising measures are linked to water usage. Where water is collected, stored and then distributed to irrigators by government agencies the taxes are a form of cost recovery for the capital and operating expenses of the scheme. However on a price basis alone irrigation has difficulty competing for water because it needs large volumes and the returns from sale of agricultural products is low, distorted by social and political considerations. As a result most irrigation schemes are subsidised from more broadly based taxation systems. This subsidisation can usually be justified in terms of overall social equity. However the unfortunate result of these subsidy schemes, where the user does not pay the real price for the water consumed is that the water users themselves cause distortions in the economy. Over time very uneconomic or environmentally damaging practices become entrenched.

Common sense may suggest certain traditions or practices should be stopped or changed but these changes may involve sufficient upheaval and social dislocation that there is not the political will to force a change of activities. As a result subsidies and environmental damage increase until only drastic measures and devastation, or payment of large compensation, or even revolution can bring about sensible change. For example it makes no sense to encourage irrigated rice growing in an arid area where irrigation farms are going out of production due to rising, saline water tables. Yet in the Murray-Darling Basin in Australia rice growing for export is encouraged by low water costs and an ideal climate, but it is causing huge environmental damage, and particularly damage to the farms of the neighbours of the rice growers. When it is suggested water prices should rise to pay a larger part of operating costs (but no contribution to scheme debt) the irrigators pressure their local politicians for assistance. At the same time they pressure their politicians to be active on the international stage to demand entry to markets for their rice, markets which already have adequate supplies from sources where rice-growing is much less damaging to the environment. They also pressure politicians to assist their hapless neighbours with their water logging and salinity problems. Simply charging the real price for water, to cover all collection, storage and distribution costs, and the cost of repairing environmental damage would stop these questionable practices. But social upheaval of a very small part of the population would also occur.

Similar problems occur in many irrigation regions of the world. Not only does irrigation provide for national food and fibre needs, and export earnings but it also provides some employment. These benefits, plus the mistaken notion that fresh water is a free gift of nature, means that irrigation is often seen by politicians solely as a solution to problems, not as what it really is, a potentially beneficial practice which needs very careful social,

economic, environmental and political management. Without careful management irrigation destroys itself or its neighbours by water logging, salinity, pests or pesticides. Many irrigation systems have been short lived, ultimately succumbing to the effects of water logging, salinity or pests. Use of pesticides will soon be added to this list.

Irrigation is not sustainable if water supplies are not reliable. Therefore decisions to permit or encourage irrigation imply an effort to provide an adequate reliable supply. Large investment is usually needed to set up irrigation systems and so a long term view must be adopted, with a recognition that success will attract further potential entrants who will also expect a share of the "naturally available, free water".

The major need for development of irrigation in areas of water scarcity is to minimise water use. Effort is needed to find attractive economic crops needing minimal water, to find and use application methods that minimise loss of water by evaporation from the soil or percolation of water beyond the depth of the root zone and to minimise losses of water from storage and delivery systems. For example it is common for good irrigation land adjacent to delivery canals to be waterlogged, indicating severe leakage from the delivery system and loss of both productive land and water. If the real price is paid for water, investors may be willing to lend funds for leak reduction and maintenance. If leaks cannot be reduced it may become uneconomic to continue use of a particular delivery system. Land holders taking delivery from such a system would then need to change their land use practices.

Use of irrigation implies water scarcity — at least for part of the year and for the crops that land holders wish to grow. However in some water scarce areas irrigation may not be an optimal use for the available water, but there will always be potential users desirous of irrigating. In these cases there is a need to discourage irrigation by suitable pricing mechanisms or by regulation. However as mentioned earlier once a practice is established it is difficult to change, particularly by regulation, because regulation needs a person (usually a politician or an appointed manager) who is subject to many competing arguments from vested interests, to change the regulations. Price changes, made gradually, can often be more easily implemented and would have the added benefit that they would discourage waste and inefficient water use. However the rate of price change must be large enough to have real effects. It must be much larger than the inflation rate, and implementing such price increases is difficult. During a period of dramatic change such as this, there is a need to provide some support and encouragement to farmers to move from their traditional high-water demand cropping and irrigation practices to modern, reduced demand systems and technologies, particularly where farms are small and the farmers are poor and have limited education.

4.5.6. Water self reliance

In a sense this is the oldest system of water management. Individuals collect water to meet their own needs. Modern developments, particularly urbanisation and intensive irrigation farming have led to development of broad scale water collection and distribution enterprises, many of them government run. However in areas of water scarcity there is a need to change thinking back, not to total self reliance, but to taking responsibility for your own water. This may mean greater emphasis on self reliance but it should also lead to development of cooperative institutions and a legal framework with sufficient flexibility to adapt to changing circumstances.

The legal system needs to serve the interests of both the majority and individuals so that no-one is disadvantaged for the gain of others. This is a very idealistic requirement but as demands for access to a finite resource continue to increase such a system will be necessary to avoid ongoing resentment, conflict and violence.

4.5.7. Gender issues

This is a delicate subject as it is impacted by cultural and traditional sensitivities. However, it is important because in most parts of the world water collection is carried out by women and children, but funding, institutional and infrastructure development are largely in the control of men. For many families in regions of water scarcity the major expenditure of labour is on water collection, either by animal power or by family members. In many of these situations labour use could be reduced by development of innovative water collection schemes. Unfortunately if those who provide the labour are permitted little or no input to the thinking about possible innovation the chances of finding more effective, less laborious water collection methods are limited.

There is a need for widespread education on all aspects of water — on methods of collection and storage, water quality and hygiene, the need to guard against contamination etc. In the 21st century many of the traditional methods of water collection and storage are very inefficient and wasteful of labour — mainly female labour.

One of the approaches that could encourage education on water issues is emphasis on the benefits for the whole family of developing more efficient, less labour intensive methods of water collection and storage. The cost of small plastic pipes is little more than the cost of electric wiring. Why do most homes which do not have a connection to a safe water supply have connection to electricity supply? Is this a gender issue? Probably.

4.5.8. Planning for optimal water and land use

In many political jurisdictions water and land go together. Water in rivers is often shared between land holders, either equal shares for each individual, or on some proportional basis, such as an amount related to the size of the landholding or the amount of landholding potentially irrigable. However, no matter what the system, human nature is such that any system adopted will be seen to benefit some and disadvantage others. Therefore there will always be pressures to change whatever system is currently in place.

When opportunity is available, such as during development of an irrigation system, or when major political changes are occurring, it is wise to examine the existing system and perhaps to attempt to devise a fairer system. Since there can be no perfect system, an adopted system needs to be seen to be fair by the majority of potential users, not just by actual current users. This means the systems adopted will be different from place to place and from time to time, depending on the cultural and political environment.

4.6. International issues — treaties between sovereign states

River basins and aquifers are no respecters of arbitrarily drawn political boundaries. Some water resource management systems are contained within single political jurisdictions

(notably island states) but other water managers may need to work with resources which originate in another state, or that is precipitated within their state but naturally supplies another state. As demands for fresh water increase there is a growing desire to utilise larger proportions of any available resource. This inevitably leads states to be reluctant to allow water to leave the area of their jurisdiction, or alternately to expect that rates of flow that have historically crossed a boundary into their jurisdiction will continue to flow into their area in the future.

It is to the advantage of every state to monitor the flows crossing its boundaries and also to enter into water resources agreements with its neighbours. Agreements or treaties preferably should be written in terms of proportions of historically measured flows rather than in absolute amounts, with provision for monitoring by both parties. Since sovereign states are usually reluctant to permit neighbours to have free access to their territory, monitoring of water resources quantities in a neighbouring state's part of a basin or aquifer is usually not possible. However there can be no substitute for long term factual information (which is accepted by both sides) on the movement of water across a boundary. Such information can provide an invaluable basis for future discussions, negotiations or appeals for fair dealing.

Water has in the past been a cause of serious international disputes and is likely to become a frequent cause of tensions in the future, particularly in regions of increasing water scarcity. For example access to the water resources of the Jordan River Valley has been a (perhaps minor) contributor to tensions between Israel, Jordan, Syria and Palestine. The demands on this limited water resource must increase as population and living standard expectations rise. In recent years, some agreements have been reached on development of the resource. However continued discussion, flexibility, goodwill and cooperation will be required in the future as the expections and demands for water grow differently in each of these states.

Another obvious example is the increasing demand for water in the Turkish and Syrian parts of the Euphrates–Tigris basin. A large proportion of the Euphrates-Tigris water resource originates from precipitation within Turkey, but this basin provides most of the water resources of the downstream state of Iraq and some of that of Syria. If the people of Turkey expect to make full use of the water precipitated on their territory the water passing into the downstream states will be reduced, having large effects on the populations and the economies of those downstream states. Discussions (and hopefully agreements) are needed now and development in the future will need to be on a cooperative basis if hardship and conflicts are to be avoided.

In Central Asia the disaster of the Aral Sea is now being addressed by cooperation between the states through which the Syr Daria and Amu Darya flow. This is a good example of international cooperation.

4.7. Conclusion

It has been shown that there are many issues to be considered in coping with water scarcity, in addition to the obvious technological issues of where to find more water and how to make more use of the water we have. Concepts of ownership of the water resource are very

important. These affect individuals rights to access water and issues such as who will manage the resource, and their legal authority. Since water supply infrastructure is large and expensive, investment is usually needed for its development. Investors are unlikely to be interested unless there is some likelihood of long term stability of management of the resource, backed up by a relatively fixed legal system and some positive economic return. The legal system needs to take account of local traditions and customs and have widespread acceptance in the community. Any legal system for apportioning rights of access to water resources needs to incorporate provision for the number of users who have a right of access to water to increase over time. A given of the 21st century is that population increases and expected standards of living rise, both of which put increased pressure on management systems which have been developed to cope with water scarcity.

5. Surface water use and harvesting

This chapter deals with ideas for maximising the surface water availability at a location for human use. The use of the water may be for domestic or industrial supply or it may be for crop growth for production of food and fibre.

5.1. Large and small scale projects

5.1.1. Definitions

"Large" and "small" are relative terms. However it is important to define them because systems management of water resources are usually different depending on the scale of the entity being managed. "Large" usually refers to projects where large volumes of water are involved and supply from the system is consumed by many users. However it can also refer to projects which have large capital requirements and sometimes to projects which operate over large regions. "Small", on the other hand typically refers to projects where the beneficiaries are limited in number, say to one or a few households or farmers. They are usually projects where the capital requirements are quite limited.

5.1.2. Objectives of water use and harvesting

In general terms the usual objectives for water management in regions of water scarcity are (1) to ensure enough water for survival at all times, and after this requirement is met to maximise the possible benefits which the remaining water can provide, (2) for household comfort and well-being, (3) for food and fibre production and (4) for protection of the natural environment.

These objectives are almost always in conflict with each other and so compromises are usually required. The conflicts are increased by the numerous different sub-objectives of the individual water users and land holders. For example it is not possible to maximise the availability of water to households while maintaining the completely natural flow of the river from which household water is drawn. Similarly householders may wish to have a secure supply of water for the whole year, but irrigators wish to maximise their water use by crops during the growing season and accept some water shortage and hardship in the non-growing season.

Conflicts will always occur because there are many users, with diverse interests and aims, all needing to obtain their supply from a single, limited (scarce) source. There is large potential for inequities of supply and for those with power to dominate and take a large share of the limited resource. Similarly inequities and less than optimal water use tend to be encouraged by inflexible political, institutional, or management systems. As with most technologies, efficient water resources use and management schemes can change rapidly and rigid institutional arrangements can often stand in the way of the changes that may be needed to develop or encourage the "best" methods of allocating water to the many potential users.

Waste of water and inefficient water use are usually considered to be states to be avoided. However in times of drought a wasteful or inefficient water use system can often, with considerable effort, be temporarily improved to allow greater use to be made of the limited water available. On the other hand a totally water-use efficient system may contain no flexibility for temporarily increasing supplies or for surviving with a lesser supply, and may fail completely. Decisions concerning how "efficiently" a system should be expected to operate, and whether or not the "inefficiency" can provide a drought "safety net" must depend on local cultural and social expectations and the physical layout of the resource and of supply points.

Water scarcity should encourage lateral thinking and flexibility in approaching water supply needs. If water is scarce, should we continue to grow our staple food, which has a high water demand, or could we grow an alternate, higher value crop which consumes less water, and purchase our staple food from elsewhere? Can we develop a taste and tolerance for a basic food which can be grown with less water? Is the water demanding industry really needed in this water-scarce region? Can we develop an industry which has more modest water requirements? Can industry recycle its water so that its actual consumption of our precious resource is reduced to near zero?

5.2. Reservoir management

5.2.1. Need for reservoirs

Most water supply schemes need to incorporate reservoirs. These may be surface storages or sub-surface aquifers. The function of the storages is to smooth out the natural variability of the hydrological system to allow human activity to be supported by a constant, or a regular, seasonally varying supply. Where water is scarce it is most unlikely it will be possible to take water on demand from the natural system. In times of high flow (either surface or subsurface) it is often possible to extract whatever water is required. However in drier times the natural flow is likely to be significantly lower than the expected extraction rate. Hence surface or subsurface reservoirs serve as temporary storages, capturing high flows whose water can then be available for use during periods of low natural flow.

Reservoirs need to be sited to minimise non-beneficial leakage or removal of captured water. For example a sub-surface reservoirs (aquifer) should be located where there can be large inflow but minimal outflow of water. Making effort to encourage recharge of an aquifer which quickly transmits water to the sea makes little sense. One needs to be found where water is trapped in the local region, and which can then be

extracted for later use.

Surface reservoirs need to be sited to minimise evaporation and seepage. This means the geology needs to be investigated to attempt to ensure seepage will be small. Evaporation can realistically only be minimised by keeping the surface area of the reservoir as small as possible. Reservoirs should be located to have a maximum volume/surface area ratio, otherwise a large fraction of the captured water will be lost by evaporation. In a region of Australia where the annual pan evaporation is about 4 m, one of the reservoirs providing water for a town of 30,000 people makes beneficial use of only 20% of all its stored water, the remainder (80%) evaporates. If evaporation could be reduced by just 25% the water supply could be doubled. However at this time, no practical strategies are available for reducing evaporation from large reservoirs. The only possibilities are at the planning stage to choose a site for the reservoir where the storage will be deep and have minimum surface area.

Silting is another opponent of maximizing water use. Over time surface reservoirs capture almost all the sediment carried by inflowing streams. Care is needed to site reservoirs where the sediment load of streams is small or provide a sediment trap upstream of the reservoir. The sediment trap will need regular cleaning if it is to function effectively. This is quite possible for a small reservoir which is supplied from only one stream but for large reservoirs it is usually unrealistic because inflow rates may be very large and from many streams. In this case the only means of preventing reservoir silting is to improve soil conservation practices by good land management and channel protection.

5.2.2. Water scarcity management

There are many opportunities for management of water in an environment of general shortage. Some of these possibilities for good management of a scarce resource are dependent on availability of capital for investment in fixed infrastructure. These opportunities usually need to be grasped at the planning stage. Their capital intensive nature means they are fairly inflexible and therefore are unlikely to be changed significantly in the near future. This means that good long term planning is needed, but this planning needs to avoid focusing on a narrow range of water use opportunities. The chances of major socio-economic or technological changes in the short-to-medium term are high and therefore narrow range or single use capital infrastructure may be a serious impediment to beneficial water management in an as yet unforeseen socio-economic and technological environment. For example there is a move away from having large storage reservoirs as the major investment of new water development projects. Moves are towards larger numbers of smaller scale water storages since these offer many more management options and particularly localised management, which is rarely possible with projects dependent on a single large storage. In overall terms a single large reservoir may provide for maximum control of water, but ultimately the inflexibility of operation of such a system often means that only a very limited sector of the population can benefit, whereas with multiple small systems the potential for flexible management and spread of benefit to a wider sector of the community is large.

Another benefit of smaller systems is that stratification and eutrophication problems can be more easily managed in small reservoirs than large ones. Overriding all these considerations must be the topography of the location. Some landscapes lend themselves to

multiple reservoirs, others do not. Large reservoir development depends on having a suitable dam site in the region.

At the operational management level there can be many opportunities for improving water availability and for improving security of supply. These two benefits are usually considered to be opposed – to increase security means more water must be held in reserve and so supply must be decreased. In a general sense this is true but with careful consideration of all the factors which influence supply, sensible flexibility of management can lead to a significant increase in one of these benefits, with no reduction of the other. Understanding of natural processes such as the occurrence of precipitation in time has enabled the development of statistical techniques which better reflect the natural processes and which can be used in flexible modes to mirror local operations and increase the benefits to be obtained from a resource. For example conservative thinking combined with only simple analytical techniques often suggests that the best management policy is to keep a reservoir as near to full as possible at all times. However it may be that more adventurous management, which may increase water use by 25% (and reduce losses of water from the reservoir by seepage and evaporation by 10%) may lead to crop failure one year in 10. The overall increase in productivity from such management may be anywhere from 15 to 50%. However, introduction of such a scheme would need to be accompanied by an ongoing education program to encourage water users to build up a reserve from their increased returns, to allow them to survive in the years of failure.

There are many reservoirs around the world which are full or near-full most of the time, yet almost all reservoirs were originally designed to become near-empty more than once during their life. Unfortunately there is too little communication between reservoir designers and reservoir operators, and much of that communication is via politicians who tend to see empty reservoirs as some indicator of evil, rather than the near empty reservoir as an item of infrastructure providing optimal performance. A whole science of "risk management" has developed in recent years. Its aim is to analyse risky operations so that all risks and potential benefits are considered and the best overall outcome is achieved. The key to good risk management is consultation with all interested parties and complete openness in all decision making. Success of reservoir planning, management and operation depends very much on education of, and ongoing communication with affected parties, be they water users, system operators, local landholders and business operators or neighbours.

Water resources systems are often seen by politicians and the population as preventers of drought. They are not, and water resources planners and managers must educate their "masters" and "customers" of this fact. Water resources projects can supply drinking water over drought periods but they are rarely, if ever designed to supply irrigation water during prolonged droughts. Rather, water resources projects aim to improve human comfort and productivity in regions of water scarcity. However there must be the recognition that every few years all regions will experience much drier conditions than usual. During these droughts water availability will be very restricted and the normal productivity of the land will be suspended. However, the very much increased productivity that the water resources project has provided in other years (perhaps 8 or 9 out of 10) will more than cover the losses of the drought, provided all water users manage their own resources (bank balance, food bank, stock numbers) sensibly, with this reality as a central feature of their management strategy.

Improved analysis of water resources statistics and development of optimal management strategies has been mentioned here. The detail of these approaches is not covered in this book but readers should refer to standard texts on this topic (e.g. Salas, 1993; McMahon, 1993). Analysis and management strategies are continually improving and so the above list may be appropriate in 2000, but better materials are likely to be available in later years.

5.2.3. Operation of single and multiple reservoir systems

Here we should use the word reservoir in its broadest sense. That is we will include all water storages including surface reservoirs, natural lakes and groundwater aquifers. These reservoirs may be replenished naturally, or they may be pumped systems or even storages built up from desalting of brackish or sea water.

Without doubt the operation of several linked water sources, rather than a single reservoir system, offers the water manager many options and flexibilities with numerous opportunities to maximise the potential availability of water. This applies to all water resource situations, not just to regions where water is scarce. However the cost of this increased flexibility of management is a very large increase in the complexity of the operation of the system and a very much increased possibility of management of the system being sub-optimal. However there are very large advantages to be gained from multi-reservoir systems, particularly where the reservoirs within the system have different water sources. For example a system with a river-fed surface reservoir, whose storage level depends on recent precipitation and a groundwater system which varies only with long term variations in precipitation has many advantages. High rates of extraction can be obtained from the surface reservoir but only for limited periods, whereas the groundwater can provide a medium level of extraction for very long periods. Similar advantages can be obtained from inclusion of desalinated water, renovated waste water, or urban stormwater. Surface water can often be supplied at low cost. Groundwater may involve larger costs for pumping. It may be efficient to design a system for surface water supply only, with high-cost groundwater only to be used in emergencies, such as prolonged droughts, when the surface supply is exhausted.

Multiple reservoir systems also offer the advantages of redundancy. Provided there are multiple water delivery pathways the system will not be shut down by any single failure of a reservoir, a pipeline or a control valve, and therefore the security of supply can be very high.

5.2.4. Groundwater recharge

Where groundwater is an important source of water there can be considerable advantages in encouraging recharge of the aquifer. Care is needed to protect aquifer recharge areas from land use changes that can decrease the recharge. It is well established that increase in quality of vegetation, by reforestation, improvement of grazing vegetation or in some cases by introduction of cropping, generally increases infiltration, but also increases transpiration and therefore reduces recharge and runoff. Therefore care is needed to allow for the effects of such surface changes on the groundwater availability or to ensure that the vegetation characteristics of the recharge area are not changed. Change from native vegetation to

cropping may lead to increased recharge because cropping involves leaving the soil fallow for part of the year. However the actual effects in any location will depend on the vegetation and crop types and rotations, the soils and the climate of the region.

Surface reservoirs can be used advantageously to increase recharge by holding water over a recharge area for some time, or by diverting water to spread it widely over a recharge area. However care is needed to ensure this does not encourage increased evaporation and a large net loss of water from the system. Precipitation is the source of all fresh water and in most situations the surface and groundwater resources are interdependent. Encouragement of recharge may mean a reduction in available surface water further downstream. Conversely impounding surface water may diminish recharge direct from the stream-bed downstream of the reservoir and hence may reduce the groundwater resource.

5.2.5. Design and management of water resource systems

Design and management of water resource systems in areas of water scarcity need particular characteristics. Since water demand in such regions will always exceed supply, and since social, economic and technological conditions are continually changing the systems need to be developed for maximum flexibility of operation. Installation of a single large reservoir to serve a large number of diverse uses in a region where new ideas and adventurous attempts to increase productivity per unit of water need to be encouraged is unlikely to provide for the real needs. There will always be some inflexibility of thinking among those given responsibility for water releases and if this responsibility lies with a single manager or management body this inflexibility tends to become entrenched. However with numerous managers it is likely that one or more will be flexible and encourage experimentation. When the results of flexible thinking are seen, users of water controlled by other managers will demand more progressive practices.

Another need for water projects is the careful integration of design and management. Management flexibility will always be limited by the fixed assets of the system, and so there is a need for managers to be involved with design as much and as early as possible.

Management plans need to be part of the original design. Similarly ongoing education programs for both managers and users also need to be set up as part of the initial design. Participatory management of a resource by all interested water users should begin at the planning stage. Such arrangements can be very cumbersome and so some kind of consensus or representation scheme needs to be devised that is sympathetic to local cultural expectations. It is common for education programs to be run at the inception of a new capital project. However it is difficult to maintain enthusiasm for such programs once a project begins operation. Without an ongoing commitment to education projects tend to have fixed operational programs and slowly run down. Continuing education is needed for newcomers to the project and to continually introduce new ideas and new technologies to the community. Flexible thinking regarding water needs to be part of school education since the children will be the users and managers of the next generation. It is much easier to educate the young than the middle aged who have become fixed in their ways.

As time passes and management (release rules) of reservoirs changes little by little there is a need to re-analyse the whole management system. Unfortunately this is a rare

practice. However a system is usually designed to maximise water use with a given set of release rules. If these rules change over time, and they usually will, the system will then probably make less than optimal use of the available resource. The system should periodically be re-analysed with the current operating rules, so that adjustments can be made to these rules, to make better use of the water. Wastage as a result of changes to operating rules, without a complete re-analysis of the system is common. The work needed to re-analyse the system is quite small, but persuading users to adopt slightly different practices to maximise benefits from the system is a much larger task which must not be (but often is) omitted from the implementation plan.

5.3. Control of water losses and non beneficial uses of water

In regions of water scarcity there should be strong motivation to prevent waste of the precious resource. There are many ways in which water is wasted. Some of these are relatively easy to prevent. In particular losses that occur once water comes within the sphere of man's control should be preventable. Other losses, such as evaporation and removal of flowing water by infiltration into stream beds are, in general, very difficult to prevent. The major types of wastages and possible strategies for their control will now be discussed.

5.3.1. Location of losses

When it is thought that significant volumes of water are being lost unaccountably from a system it is worthwhile making some effort to determine exactly where the losses are occurring. This requires some means of measurement of flows at a number of locations within the system.

Reservoirs are a common site for major losses. To check whether significant losses are occurring there is a need to measure, or estimate fairly accurately, all the observed movements of water and to conduct a simple water budget for a couple of years. Evaporation can be estimated by operating an evaporation pan adjacent to the storage, and making allowance for the higher loss from the pan than from the lake due to differences in energy transfer within the lake and through the sides and base of the pan. If the sum of all the inputs and outputs of water do not match the observed change in reservoir storage volume there must be some unaccounted movement of water. It is usually assumed that there will be a few percent of inflows lost by seepage, but much larger, unexpected seepage losses are possible. However, this seepage may not be a loss if the water moves into a good quality aquifer from which water is being utilized. However the water is certainly lost if it is added to saline groundwater, or if it moves to an aquifer from which it cannot be recovered.

Conveyance and distribution systems are often the source of large wastage of water, but some of it can be prevented. In many situations water is transported to the point of use via the river bed downstream of a dam. In regions of water scarcity these river beds will usually absorb huge quantities of water. Similarly, unlined delivery canals may also leak large volumes. Canals can be lined with clay materials, buried sheeting, synthetic membranes or concrete. However, unless great care is taken during construction and with

maintenance, the leakage is usually reduced only by a small amount, perhaps by 20 - 40%, (Rushton, 1986), and any form of lining is very expensive. However it may be that most leakage occurs from a short length of a canal and in this situation remedial action such as some form of lining of this short section may make economic sense. Where water has very high value it may be economic to deliver it by pipeline. Provided the pipeline is maintained properly, leakage can be practically eliminated.

Water use practices are a major source of wastage. Factory production processes and cooling systems which do not recycle can be very wasteful of water. In many parts of the world recycling of factory process water is now mandatory. The high cost of recycling systems themselves encourage reduction of losses by forcing factory managers to adopt processes which induce minimal water use and pollution. Evaporative cooling systems avoid problems of raising the temperature of stream water, but they consume large volumes of water. Where water is scarce evaporative cooling is unlikely to be an optimal practice since heat is dissipated by the change of state of water from liquid to vapour, and the vapour is lost from the system.

There are many opportunities to save water by changing irrigation practices as outlined in section 8.8. In traditional irrigation enterprises basin, flood and furrow irrigation are common. In most cases it is difficult to properly control the amount of water application, and so, much water flows beyond the root zone. In flood and furrow irrigation large amounts of water may flow downstream out of the field. Farmers need to be encouraged to change their practices since it is possible, using other irrigation techniques to obtain equally high yielding crops with less water application.

Similarly sprinkler irrigation can be very wasteful if used in windy daytime conditions in hot and dry climates. Wherever possible irrigation water should be applied in the evening and in windless conditions. Drip irrigation tends to have the least loss of water but it needs careful management and maintenance, is expensive to install. While it can be used to save water, particularly for irrigation of trees and shrub crops it is not usually suitable for irrigation of broadscale field crops such as cereals.

One form of encouragement of the use of such water saving practices is to stop subsidising water supplies and to charge the full cost of collection and distribution of the water plus the cost of maintenance and operation of the system. As discussed in chapter 4, these measures have to be implemented progressively while introducing supplementary measures to help farmers and water users to adapt and maintain the viability of their enterprises.

5.3.2. Reduction of evaporation

There is no effective economic way to reduce evaporation from large water bodies. At the planning stage reservoir locations need to be chosen to minimise evaporation – by ensuring the volume to surface area ratio for the reservoir is a maximum.

Evaporation can be reduced from small, vertical sided reservoirs by providing a roof to shield the reservoir from solar radiation or by covering its surface by light coloured floating blocks. Solar radiation is the main source of energy for evaporation so any shielding can be helpful. Floating covers are only effective if they are not porous and if their upper surface can be kept dry. If water splashes onto the surface of floating blocks

there will be little or no reduction of the evaporation. Monomolecular cetyl alcohol, which forms a layer one molecule thick across the surface, can be very effective but the integrity of the protective layer is spoiled by any wind. Similarly oils can be used but they can introduce toxicity problems, so that care is needed to choose materials appropriate for particular applications.

The most effective means of evaporation reduction is to minimise the water surface exposed to the atmosphere and to the sun. Deep storages are to be preferred. Subsurface storage can be very effective for evaporation reduction. However with subsurface storage there will always be seepage losses and so these must be weighed against the gains from evaporation reduction.

Evaporation from the land surface can be reduced by mulching the surface or by tillage to keep the surface capillaries broken. Similarly, infrequent watering to completely fill the root zone of the soil can use less water than more frequent small applications which only wet the upper part of the root zone. Each water application wets the surface and encourages evaporation at least from the top few centimetres of the soil.

5.3.3. Support for reduction of waste of water

In regions of water scarcity, reduction of wastage of water should be part of the thinking and awareness of every individual. It needs to be taught in families to small children and in all formal education systems. In many societies the connection between simple traditional activities and waste of a precious resource is not realised. There is a need for continuous education programs to ensure everyone believes the loss of a single drop of water is a cause for sadness and concern. Most villagers are aware of how precious every drop is, but there is a need to educate city dwellers, and even some village folk. Commitment is needed from society leaders to ensure ongoing educational programs. A requirement to pay the full cost of water supply can reinforce education programs. Households for which all water must be carried several kilometres by its members are usually very parsimonious in their water use. However city dwellers who have piped water either free or at little cost are encouraged by the system to be profligate water users (wasters).

Education programs (see chapter 10) should be accompanied by campaigns oriented to professionals in the diverse water use areas, where financial incentives could be offered to users who adopt water saving tools and practices. Water recycling in industry, changes in irrigation methods or adopting water efficient shower heads and toilet flush, and cisterns in households, all require investment by the users. These users may be aware of the water saving advantages but they will be hesitant to adopt those new tools unless incentives are available to encourage them to move in such a new direction. Similarly, providing the users with easy information about how and where to purchase such tools or to get help to make better use of innovative practices is also relevant.

5.4. Water harvesting

Water harvesting refers to methods used to collect water (1) from sources where the water is widely dispersed and quickly changes location or form and becomes unavailable or (2) that is occurring in quantities and at locations where it is unusable unless some intervention

is practiced to gather the water to locations where it can provide benefits.

There is a number of water harvesting techniques that are practiced in many of the water scarce areas of the world. However there are many other techniques that have developed from local necessity in sympathy with the local physical conditions and customs that could be adapted to benefit populations in other water scarce locations. A large number of such practices have been described in a number of papers in Pereira *et al.* (1996) and by Khouri *et al*. (1995) and included in the bibliography list. Other complementary information is provided in Chapter 7. A number of the widely practiced techniques will now be discussed.

5.4.1. Rainwater collection

Rainwater can provide a considerable water resource, not only in humid regions but also in semi arid and arid regions. Large volumes of water flow from roofs. In many regions roof water has not been collected because traditional roofing materials did not permit easy collection, and storage of collected water was difficult and expensive. However in recent years the ready availability of some form of roof sheeting and innovative ideas for water storage have made roof water a serious water resource consideration. There is a great need to encourage its use and to teach simple, low-cost means of collecting water from roofs, and constructing suitable storage facilities. For example in the dry north east of Thailand storage containers (jars) were constructed by householders from concrete reinforced with wire netting to hold volumes ranging from 100 up to 3 000 litres. Roofs were modified slightly to facilitate collection of all but the first few litres from each rainfall event. These innovations radically changed the lifestyles of the majority of inhabitants of the region, by providing enough water for in-house uses over the dry season. Measures may be needed to keep insects (mosquitoes and flies) away from the stored water to avoid increases in diseases carried by these creatures (malaria, dengue fever). This can be achieved by covering the opening of storage jars with mosquito netting or by carefully disinfecting the stored water (with bleach).

In many regions of the world, rural populations continue to use some traditional methods for rainwater collection for their households and for animals. However, there is a need to pay better attention to these systems and support those populations to improve their primitive systems, to make them more efficient and safe with respect to human health. In such rural areas it is very likely that the villagers are willing to adopt some kind of innovation. Existing systems usually have the potential to be improved and to continue in use for a long time, constituting a valuable alternative to more sophisticated systems, which are generally more difficult to implement and maintain.

5.4.2. Terracing

Terracing can be used to collect water for two purposes. Firstly a horizontal surface reduces runoff and maximises the infiltration of water into the soil. If the soil surface is kept tilled and free of vegetation except for the desirable crop, almost all rain falling on the terrace will be used for crop growth. In regions of low rainfall, soil water can be stored over long periods provided the soil surface is kept tilled or mulched and vegetation free. Thus it may be possible to store up to 2 years rainfall to obtain one cereal crop. If there are several

terraces down a hillslope it may be possible to grow a crop on alternate terraces each year. Infiltration terraces can support soil water storage to make a crop viable each year where the rainfall total is sufficient. It can also provide for perennial tree crops when these are able to develop extensive root systems, as typically occurs for olive trees in semi-arid Mediterranean areas. In some cases, the cropped terraces are downslope of a runoff area and may infiltrate more water than that provided directly by rainfall, as occurs in the *meskats*, which are traditional in Tunisia (Missaoui, 1996).

Secondly terraces can be used as temporary water storages to reduce flow velocities of surface water and prevent erosion. The slow flowing water on the terrace may then be directed into a storage facility (excavated hole or small dam) for storage and subsequent use. Without the terraces and their associated flat slopes small storage facilities usually become filled with silt in a very short time. Terracing helps keep the soil where it is needed and useful and provides silt free water for storage.

5.4.3. Small dams

In regions of high evaporation, small and shallow dams are usually a cause of high evaporation losses. However in groundwater recharge areas, small dams, or even low embankments across floodways, can be used to increase aquifer recharge. On grasslands used for grazing the encouragement of infiltration by low embankments which reduce flow velocities and hold water for a few hours after rain events can increase soil water and greatly increase the time after rain that water is available to vegetation roots. By this means it may be possible to double annual biomass production in semi arid regions.

A major difficulty in management of small water supply dams is siltation. Small dams will usually be constructed on small headwater streams. These are often steep and can carry large amounts of silt. If the land surface upstream of the dam is in its natural state the silt and suspended solids load may be small, but usually the upstream area will already have been heavily affected by human activity. Most human activity increases erosion and sediment loads in watercourses. Exceptions occur where large efforts are made to keep erosion to a minimum.

If no attention is given to sediment control most small headwater dams will fill with sediment within a few years, with almost total loss of the water source and the effort and/or capital invested in the construction. The most effective erosion prevention is complete protection of the upstream land from human activity (including grazing of their livestock animals). This is usually unrealistic. Next best is to take intensive measures to prevent surface and stream channel erosion. Third best is to provide a sediment trap upstream of the reservoir. This will usually take the form of a region where flow velocity will be reduced almost to zero so that sediment will be deposited before the water flows into the main storage. Sediment traps need to be quite large to reduce velocities sufficiently for suspended materials to be deposited. It may be possible to achieve this with a wide horizontal section in the approach channel. The sediment trap must be constructed to allow easy maintenance. The sediment will need to be removed periodically (perhaps as often as annually) and so the trap must be arranged so that locally available removal equipment can be used to clear the basin with minimum effort and cost. It is obvious that a sizeable proportion of the total capital cost of the small dam must be invested in the sediment trap (perhaps 20% of the total cost) and that a large proportion of the ongoing maintenance cost

(perhaps 80%) will be used for clearing the sediment trap.

An alternative to an active sediment trap is to allow the sediment basin to fill and then to plant a hardy crop on it, usually olive and palm trees. Provided this cropped surface is large, it can continue to remove sediment from flows into the reservoir. However it must have a large surface area, otherwise sediment will pass over it and enter the reservoir. Good examples of this technique are the *tabias* and the *jessours,* which are traditional in North Africa (Missaoui, 1996; Prinz, 1996). These systems not only provide for life support of the rural populations but also create beautiful landscapes in quite arid environments.

Animal and human access to the edges of reservoirs behind small dams is another serious cause of damage to the storage capacity and to the water quality. While animals wading and wallowing at the edge of the reservoir may be thought to be kind to the animals, this activity will quickly destroy the water resource. Continual stirring up of edge sediment by the animals reduces the water storage capacity, causes the stored water to be continually turbid, and introduces dangerous bacteria and nutrients. Small reservoirs should be securely fenced and water should be supplied to both humans and animals at valved collection points and drinking troughs outside the fence. When required, power to lift water to these points can be supplied by small hand pumps, animals or a simple wind mill.

Without careful consideration of sediment management and provision of resources for this activity most small headwater dams will be condemned to early failure. In most cases combinations of the above measures will be needed to prevent loss of the reservoir by siltation.

5.4.4. Runoff enhancement

In places of water scarcity where the availability of water needs to be increased it is possible to enhance runoff from rainfall events by partially sealing the soil surface. This can be done by applying surface sealing materials or by compacting the soil surface. Application of surface sealants (such as bitumen) is expensive and provides increased runoff for only a limited time. The sealing materials usually weather rapidly and are penetrated (from below) by vegetation so that their integrity as a surface seal is usually lost quite quickly.

Compaction of the surface requires labour and perhaps some machinery but compaction tends to be longer lasting than adding surface covering materials. In some cases, it may be necessary to import aggregates to mix with the surface layer (perhaps to a depth of 20 mm) to provide a high density material at the surface, and to add some cementing agent to prevent the surface layer being removed by wind and water. The surface can be compacted by one or two passes of machinery, by using hand tamping or by the passage of many feet, particularly hoofs of sheep and goats. Compacted natural soils, or modified soils can have very low infiltration characteristics and provide up to 80% of all rainfall from a storm as runoff. Even small areas can deliver significant quantities of water. For example a 12.5 mm rainfall event could produce 1000 litres of water from a 100 m^2 compacted area.

Prepared runoff enhancement surfaces need protection from damage and general maintenance to preserve their impermeable characteristics. There is also a need for collection of the runoff in a suitable container from which it will not be lost by seepage or

evaporation. The modified surface and any delivery channels need to have flat, but definite gradients to move water to the collection point without causing erosion of any of the surfaces. Care is needed to choose enhancement materials which are non toxic and do not produce toxins as they break down over time.

Runoff enhancement is often practiced to grow trees and vegetables. Water can be gathered from a semi sealed surface to flow towards a tree or small vegetable plot to infiltrate the soil in the vicinity of the plant roots. In this way water availability for crops can be increased many fold over the natural rainfall to provide sufficient for growing essential life-support or high value crops in regions of water scarcity. Missaoui (1996) and Prinz (1996) describe many of these runoff enhancement arrangements, generally called micro-catchment and medium-sized catchment water harvesting systems.

5.4.5. Runoff collection

In undulating to flat terrain where runoff collects into large numbers of very small stream channels, the available water resource may be quite large, but its diversity makes it difficult to use. Under these circumstances it is often possible to capture part or all of the flow in a small channel and divert it to another channel. Diversion channels which run almost parallel to the contours can be used to carry this diverted flow to a different location. If flows from a few of these channels can be gathered there may be enough water to fill an excavated hole or small dam which is deep enough to prevent loss of all the water by evaporation. The small diversion channels, following the contours, with a slight slope, can often be constructed using hand tools, or animal power, or with simple earth moving equipment such as a road grader blade. In this way it may be possible to capture flow from several stream channels, each draining a few tens of hectares, to gather water from two or three hundred hectares to a single location. Five millimetres runoff from 200 ha represents 10 Ml of water. If 75% is removed by evaporation and seepage, this is still enough to supply the in-home needs of 100 people for 1½ years. There are many landscapes where there is small relief where many small streams flow. However when these streams reach the almost horizontal surrounding land the water is dispersed and quickly infiltrates. If excavated holes were dug in the undulating terrain above the flat area, and water was diverted via near horizontal catch drains to these holes, a relatively large water resource could be available.

It is also possible to use the water that is temporarily held in horizontal catch drains and infiltrates to grow a row or two of a crop, in the bed. Such techniques are described by Khouri *et al*. (1995).

5.4.6. Flood spreading

Flood flows are a feature of all landscapes, including regions of water scarcity. A very large part of the annual flows may occur in one or two floods, but the flow is often so large that the water passes through the region and can not be used where rain fell. Some advantage can be gained from these large flows by encouraging them to spread across flat areas. If water can be retained on flat surfaces for a day or two the upper soil layers may be saturated or water may percolate downwards to replenish the local aquifer. In both these circumstances the water thus “harvested” is available for later use, in the first case for

growth of crops or to support grazing and in the second case for whatever purpose groundwater is used (Prinz, 1996; Missaoui, 1996).

Where the terrain is suitable it may be possible to restrict flow in the river channel and force water to flow over the floodplain or into an old floodway. Flood spreading by these means can most easily be achieved where the upstream-downstream gradient of the river valley is quite small. With small longitudinal gradients water forced onto the floodplain will tend to flow in the downstream direction very slowly, allowing maximum time for infiltration to occur.

Channel flow can be restricted by placement of large rocks, dams and erodible dikes in the bed or by securing a log in the stream bed. Overbank flow velocities can be reduced by construction of low banks (perhaps 30 cm high) across the direction of flow. Low, wide banks will become stabilised by natural vegetation and are likely to need minimal maintenance. However large maintenance is required after a large flood destroys the constructed infrastructure every few years. The benefits of flood spreading, where the terrain is suitable, can be quite large in terms of increased biomass production and increased groundwater resources.

5.4.7. Water holes and ponds

Natural water holes and ponds can be exploited for water supply purposes. There is a need to ascertain the source of the water – is the hole fed by groundwater or by small surface water flows after each rainfall event? If the supply is from groundwater it may be possible to treat the pond as a well and increase the extractable water by making the pond deeper and increasing the hydraulic gradient towards the pond. If the water is supplied by surface flows in a stream bed there are several possible ways to increase the water availability. One means could be to raise an embankment across the stream bed downstream of the water hole to increase the volume of water captured during each flow event. This is a kind of small dam. The embankment will need to be carefully designed and constructed to prevent its destruction in the next significant flow in the stream.

It is possible that the water hole exists because there are water tight strata below. Raising the water level may not increase the volume stored, but may supply water to the permeable strata above the natural water level of the hole. In such a case increasing the available resource may only be possible by excavating a larger hole in the water tight stratum (very expensive) or by pumping the excess water to another storage location during the brief period the water is above its natural level.

The water supply obtainable from a natural pond can often be increased by raising an embankment around the pond, or by increasing the depth of the pond. Increasing the surface area of the pond usually only increases the removal of water by evaporation, but increasing the depth of a pond can often provide significant benefits. If an embankment is to be raised, excavating materials from the pond bed and thus deepening the pond can provide the added benefit of increasing storage capacity without increasing evaporation loss. It must always be remembered that in areas of high potential evaporation, depth of water is the key to effective water storage.

5.4.8. Tanks

The word “tank” has several different meanings. In some countries, particularly in south Asia, a tank is a water hole. It is often an enhanced natural pond or it may be an excavated hole. In South India and Sri Lanka it is a small surface reservoir. These types of tanks have been dealt with in previous sections.

In other countries a tank means a constructed water container. It is usually fabricated from sheet steel, cement concrete or plastic. Such containers are expensive, relative to the volume of water they store, but they have an important set of advantages over larger, landscape-type storages. They are of particular importance where the resource is very limited and needs to be protected from evaporation and/or contamination.

As discussed elsewhere it is not possible to prevent large evaporation losses and some seepage from ponds and lakes. However small tanks, with capacity anywhere from 1000 l to 10 Ml can be totally enclosed, almost completely preventing losses. Such storage containers are worthwhile where limited amounts of roofwater are collected or where water is desalted at considerable expense. Constructed containers also offer easy prevention of contamination since access to the stored water can be controlled. This includes prevention of access by mosquitoes and other water sourced disease vectors.

For similar reasons it is also important to allow water to be removed from the storage tank only via a valve outlet. Dipping of containers into the tank or any other form of water removal inevitably leads to contamination of the water by chemicals, bacteria, insects and the catalyst effect of light. While ultra violet light has a purifying effect on water, general sunlight encourages growth of many undesirable water residents. There are significant advantages in keeping water storage containers totally enclosed.

If drinking water is to be supplied to stock it is better to pump the water to a drinking trough than to allow the animals to wade into the edge of a pond. Wading animals cause erosion, turbidity and generally contaminate the water, and so water holes should be fenced off.

5.5. Environmental issues

5.5.1. Overview

As population increases and ever larger demands are made for water resources there is a need to consider the environment of which the water resources are a part. Any human intervention, such as withdrawal of water for life support, diversion for irrigation, storage for use in dry periods, or enhancing runoff in arid regions impacts the natural flow regimes. When populations were much smaller than today and the bulk of these populations were subsistence farmers or hunter-gatherers these interventions usually had little effect on regional water resources, although there were some exceptions. However recent population increases, and changes of lifestyle and technology have meant water demands have increased to a point where alterations to natural water regimes have been large enough to seriously impact previously existing water uses and to restrict continuation of newly introduced water resource utilisation. Developments of river basin water resources have

occurred piecemeal, without basin-wide planning, and the result has often been widespread environmental damage. Devastation of the Aral Sea and the surrounding region as a by-product of upstream irrigation development is an obvious example, but there are hundreds, perhaps thousands of other examples. These range from consumption of all flow leading to decimation of all aquatic species downstream, to trapping of sediment in reservoirs and subsequent erosion of stream beds below the reservoir to consume some of the water flow energy, to salinisation and desertification of huge areas and salinisation of once fresh water due to unwise irrigation and forest clearing, etc. The list is very long.

As stated above some of these unexpected environmental effects impact on the activities which caused them but others only have impacts downstream, perhaps on the other side of a political boundary. While the benefits of the new developments may be considerable for some, are the overall benefits positive? Recent times are characterised by change but is devastation of a water resource a desirable change?

Huge financial resources are currently being consumed in attempts to overcome, or at least reduce man's damaging impacts on his own life support system – his fresh water resources. Unless great care and wise, broadscale thinking is applied to water resources, the near future will be characterised by rapidly diminishing water availability per person. The problems are most serious in the semi-arid and sub-humid regions of the earth where large land resources are available but water is very limited. Perhaps in the near future, continuation of current unwise developments in these regions will so damage the water regimes that continuation of present lifestyles will be impossible.

Therefore any thinking about increasing water availability and water, use as discussed above, must be considered in the context of environmental impacts. While the political reality is that if people are short of water then the (usually very limited) local resource will be developed to meet their needs. This approach is usually justified as being a humanitarian necessity to meet a particular need. The intention is to "only meet this existing need and to decide that needs such as this will not be permitted to develop elsewhere". Unfortunately meeting these local crises becomes the norm and the desperate needs of the increasing population for water becomes the focus of attention. The effects of the development of supplies on the overall hydrology of the region becomes a non-issue, until disaster strikes and the whole system fails because the demands for water exceed the total resource of the region. History gives many examples of civilisations which developed around a water resource which was used to irrigate crops for the consumption of the local population. Many of these developments eventually failed due to waterlogging or salinisation or both. However several major irrigation dependent societies survived over the long term as for some in China and Punjab, and those of the Nile valley. In the Nile the water and the valley soils have relatively low salt content, and before the construction of Aswan High Dam the soils were leached by annual floods (Biswas, 1980). The sustainability of several of these systems is now threatened by waterlogging and salinity due to intensification in land and water use and the adoption of modern technologies without appropriate follow-up and supporting research. The message to be learned here is that irrigation can be sustained only if conditions are suitable and there is a management system in place which is taking care to monitor conditions and has the power to intervene to modify practices at the first signs of problems developing.

As suggested above, there are always going to be political and social pressures to

overdevelop water resources, often as a “temporary” strategy to alleviate social problems which have other causes. However these "temporary" activities rarely have a closure date and the less than acceptable environmental damages become the cause of widespread disaster. Overstressing of water resources, even for short-term emergency social needs should be resisted. Repair of even short-term damage is almost always a long-term problem and continuation of the “short-term” measures usually leads to irreversible damage. For example, once the soils of a valley flood plain become salinised it is almost impossible to remove the salt. Leaching and drainage are paramount, but they are generally only viable to control salinity, not to completely reverse the problem, even if good quality water is available when the salty water table is close to the surface (see section 7.3). Then irrigated agriculture has to cope with salinity, thus accepting that yields be lower than the optimal potential. Farmers and managers are forced to adopt improved and somewhat demanding water management practices to keep the land economically productive. In fact, lowering the high groundwater to former levels is usually not a possibility and disposal of salts in the river would have severe effects on downstream water uses as has occurred for the Aral Sea case. Growing salt tolerant trees to lower the water table has a limited impact and creates enormous social problems when land provides the only livelihood for small farmers and peasants.

Short term, and indeed any, politically expedient pressures on water resources must be avoided. Examples from around the world show that an integrated approach where multidisciplinary know-how from engineering, agronomy, economics and social sciences is required in water resources development projects. Not only is it necessary to predict impacts but also to foresee how the technologies and society will evolve in the medium term. Innovative thinking is required.

Apart from these general issues there are many specific environmental issues which need to be considered in regions of water scarcity. All can be managed, but without suitable management all will bring any water resource developments undone. The more important ones are discussed below.

5.5.2. Protection of stored water

Stored water needs protection from evaporation and seepage loss and from contamination. Losses are discussed in 5.3 above. Contamination occurs mainly from human or other animal contact. If water is to be used for drinking and food preparation no direct or indirect contact with any animals should be allowed. This includes use of buckets to extract water, which have been touched by human hands. Any human or animal contact with the water, or with any surfaces which contact the water, such as buckets or water jars, or lifting ropes or wires, have potential to transmit bacteria to the water which can then cause disease in the water users. Therefore it is much better to use a pump to extract water from the storage. This applies to surface storages and tanks as well as to wells. Animals and people need to be kept away from surface storages by surrounding them with secure fencing. As outlined above, animal water can be supplied in a drinking trough. Allowing grazing or work animals to drink directly from a surface pond brings contamination and causes the water to be continually turbid.

Birds should also be discouraged from accessing water stored for drinking purposes. It is impossible to exclude them, unless the surface is small enough to be covered. However

domestic birds and large flocks of wild birds need to be kept away by fencing and frightening.

Similarly stored water needs protection from disease vectors such as mosquitoes, flies and molluscs, which are discussed in section 5.5.5. The simplest insect protection is to keep the stored water enclosed. This is particularly important for water stored near accommodation, such as in rain-water storage tanks. Having adequate water supply close to one's house is important, but if frequent incidences of malaria are the result it is probably worthwhile locating the storage at some distance.

5.5.3. Sediments

Most human activity leads to increased soil erosion. Most eroded materials eventually find their way to stream channels and into water storage reservoirs and ponds. The best strategy for dealing with sediments is to prevent erosion. Human activity, including farming and herding, involve removal of vegetation and disturbance of the soil surface. Subsequent wind and rainfall set surface soil grains in motion and those moved by water all travel to the natural drainage system, the river. Increase in sediment delivery changes the character of the river. The sediments build up on the river bed, reducing the channel cross-section and changing the hydraulic gradient. Natural energy processes will then work to develop a new state of equilibrium between bed-slope, channel cross section, discharge and sediment movement. The river channel may widen to accommodate the risen bed level, thus introducing more sediments from eroding banks, and/or the gradient may increase, to provide energy to move the increased sediment load. Whatever occurs, the character of the river channel will change, certainly downstream, but possibly upstream as well, as a result of changed gradients. Property of landholders downstream may be greatly affected. Banks may be eroded and the river may even change its course. During floods large amounts of sediment may be deposited on the floodplain, which may be beneficial, but is more likely, at least in the short term, to be unwelcome. This discussion does not apply just to perennial rivers. It applies equally to rivers which flow for only short periods, such as the wadies, and for most of the time are characterised by dry channels.

The more obvious problem produced by sediments is the loss of storage capacity of reservoirs. It is not uncommon for storages to be completely filled with sediment within a few years of construction. Loss of a storage in this manner is a very serious matter. All investment in construction of the storage is lost, but more seriously, one of the few possible locations in a region for siting of a storage is also lost, probably for ever. Where large amounts of water are available it may be possible to manage silt inflows with spillway gates and sediment sluices, but in areas of water scarcity this is not possible.

As discussed in 5.4.2 above the best means of protection of a water resource from sediment problems is protection of the land surface from erosion. This is the only measure that can be taken for reservoirs that have large catchments. For small reservoirs it may be possible to construct a sediment trap upstream of the reservoir as discussed in 5.4.2. The sediment trap will consume some of the available water resource but this may be a small price to pay for increasing the reservoir life from just a few years to decades. After an inflow event it may be possible to save the water held in a sediment trap. Within a few days most suspended sediments will be deposited on the bottom of the trap and the clear surface water can be pumped to the main reservoir. If this is not done a water volume equal to the

capacity of the sediment trap will be lost from each runoff event. The shallow character of the sediment trap means the water held will all be removed by evaporation within a few weeks, before the occurrence of the next runoff event. Since most runoff events are very small, perhaps producing little more than the capacity of the sediment trap, transfer of sediment trap water to the main storage after each runoff event could significantly increase water availability. This practice is not viable in areas where erosion and sediment yields are very high such as the Loess Plateau in Northwest China. When such unfavourable conditions occur, one of the only means of capturing surface water is to construct rock dikes across valleys. These fill with sediment and provide a flat surface for crop growing, particularly trees with deep roots to reach the water stored in the trapped sediments, as was mentioned earlier for the *jessours* in North Africa, or for what are locally called *caags* in Somalia and *warpings* in China.

5.5.4. Water quality

Water quality issues are of utmost importance where the water is for human consumption. However some aspects of water quality are of importance for almost all water uses. For human consumption bacterial contamination is of great importance whereas chemical quality is of importance for almost all uses. In regions of water scarcity where there is little or no choice of water source it is important to protect the quality of the available water, and in some cases to prevent its contamination.

Most bacterial contamination results from contacts between the water and animals, particularly humans. Human and animal wastes need to be totally separated from the water resource. It is quite common for much of the bacterial contamination of water to occur at or after its collection from its natural source. For example, water collected in jars becomes contaminated by hands which lift the jars or which haul on ropes used to raise the water to the jars. Similarly at the collection point any spilled water which drains back to the water body is almost certain to contain bacterial contaminants. Great care (and education) is needed to prevent these and many other simple causes of drinking water contamination.

In many situations household wastewater is returned to the water course without any treatment. When this wastewater becomes a significant part of the total flow (say more than about 5%) the bacterial quality of the resource quickly declines, to a point where it is of little value to any user and it can become a serious health hazard. It is imperative that human wastes not be allowed to enter streams, but that dry pit toilets be used or that simple water treatment systems such as septic tanks be interposed between households and the stream system. Without universal use of such methods the scarce water resource of a region can be completely destroyed by a few careless or selfish households.

Bacterially contaminated water can be disinfected by introduction of a small amount of bleach or by boiling. However if it is the household's responsibility to carry out its own disinfection, then health problems are likely to be frequent because disinfection is expensive and needs careful attention to detail, meaning that the protection system is likely to be much less than perfect.

Chemical contamination has many causes. The most common are contact between the water and deposits of chemicals on or within the soil and rocks over and through which the water flows. Various salts are highly soluble in water. Unfortunately, around the world,

there are communities whose water supply is contaminated with naturally occurring toxins such as arsenic, nitrates and fluorides, to name just three. These often occur in water supplies at levels too low to have an objectionable taste, but high enough to cause severe health effects in the long term. In situations where chemical contamination is a possibility the population needs to be encouraged to make alternate arrangements for drinking water, such as collecting roof runoff, perhaps in pots and jars. In the arid zone and regions with long seasonal dry spells quite large storage is required – enough to supply 10 litres/day/household member for the duration of the dry season, i.e. about 2000 litres per person.

Fine sediments, particularly those of colloidal size which produce turbidity, are often a source of contamination. The sediments themselves may be harmless but many forms of contaminants, both bacterial and dissolved salts often adhere to the microscopic particles. Allowing water to stand for a few days and then removing for consumption only the clear water from the top can avoid many of the dangers. More effective is filtering the water through sand or a membrane. Filtering can be very effective in removing all particulate contamination but it is expensive and needs use of some specialised equipment. However filtering is totally ineffective in removing dissolved contaminants such as various salts (NaCl, $CaCO_3$) which have not adhered to the surfaces of particulates.

Stored water, particularly if located near a residence, needs protection from insects and other vermin. This can be achieved by either totally enclosing the stored water or by installing and carefully maintaining insect screens.

5.5.5. The riparian ecosystem and biodiversity

Wherever there are significant population densities, or irrigation is practiced, the natural flow regime and the range of species inhabiting the rivers will be changed. Over historical time the aquatic flora and fauna have developed in concert with the flow regime. When the flow regime changes some of the species will become stressed and die off. Other species which prefer the new flow regime will then colonise the river bed and flood-plain. These changes may be seen as desirable or undesirable. In most locations, not only are the aquatic species adapted to the flow regime, but other species, including humans, have adapted their lifestyles to be at least partially dependent on the existing environmental conditions. For example where villagers are dependent on catching fish or crustaceans to provide their protein, but flows are stopped by a dam, the villagers will need to change their lifestyle dramatically to survive. All water resources development, water diversion, or use of streams to transport and dilute wastes causes changes to the environment, usually in ways that adversely affect downstream populations.

In recent years it has been realised that many of the changes produced by significant modification of flow regimes are undesirable. Policies have been developing to reduce the changes in the flow regimes such that the general environment downstream will not be drastically modified. At present it is quite unclear how much alteration is acceptable. Large debates are occurring over how close to the pre-development regime the post-development flows should be. In most situations the aquatic environments are not sufficiently understood for clear guidelines to be developed. Post development flows are being set at about 25% of the pre-development situation, with similar variability, but this is an arbitrary figure which has no scientific basis. Presumably it will be enough to support some species, but others

will disappear.

Environmental flows, the flows needed to sustain the naturally occurring species (flora and fauna), are very difficult to define and are currently the subject of vigorous scientific and political debates. For many streams maintenance of the flows necessary to support the natural systems means virtually no development can occur. In other regimes, particularly in semi arid and arid regions very little is known about possible effects of developing the very limited water resources. It is quite possible that every region would be very different. In some areas there may be little or no effect but in most arid regions any removal of the very scarce resource is likely to have large effects. These effects may not be immediately apparent but in the long term they will be noticed, but by then it will probably be impossible to reverse the effects even if there was a desire to do so. For example nesting places of migratory birds in wetlands may be endangered so that the population may be reduced by 30-40% each year. This reduction may not be noticed for some years and then by the time it is decided some remedial action is needed and changes are implemented the birds may be extinct. Similar problems can occur with many other arid zone species, particularly because they are rarely seen and therefore their life cycle is not yet understood.

Care is needed to avoid the attitude that human survival is paramount. What effects does extinction of other species have on humanity? In most cases we do not know. Therefore great care, and exercise of the precautionary principle needs to be encouraged.

In regions of water scarcity, as distinct from arid regions, the problem is much more critical. Human survival in the region may require that all water is appropriated for "beneficial use". In these situations the local population must decide whether or not the downstream environment should be preserved in a near-natural state, or whether it can be sacrificed for the development. Does it matter? There is a need to educate those who make such decisions and assist them to evaluate the total benefits and losses of such changes in local biodiversity. Most of the problems produced by such developments in the past were the result of either ignorance or piecemeal local development. However the consequences can be very large. Examples of huge environmental damage are the disappearance of fresh water inflows to the Aral Sea as a result of upstream irrigation and the hugely reduced flows of water to the sea in many rivers due to upstream developments. Reduction of freshwater flows to the sea causes changes in marine life, allows brackish water further inland along estuaries, changes river mouth species, disrupts intake of fresh water supplies for a range of supply schemes, damages or destroys mangrove forests and allows pollutants to concentrate in estuaries where previously they were dispersed into the ocean.

Relaxing requirements for environmental flows in regions of water scarcity to allow the local population to survive will usually provide only short-term benefits. The degradation produced by cutting off all flows will eventually be so large as to discourage continued settlement in the region. An example is the draining of the marshes at the head of the Persian Gulf.

5.5.6. Water borne diseases

Water borne diseases are endemic to many parts of the world. Many common ailments are transmitted via water by unhygienic or unsanitary practices. It is well known that simple cleanliness, particularly having clean hands whenever they come in contact with stored or

transported water is very important. Myriad bacteria are transferred from dirty hands to water to mouth and gut to develop into one or another form of enteric infection. These infections can be manifest in the form of a slight reduction in an individuals normal comfort level, to the other extreme of serious illnesses such as cholera, typhoid, hepatitis, dysentery or one of many other potentially deadly diseases. These problems become more serious as water becomes more scarce because there is then thought to be less water available for washing. The opposite is true. As the resource becomes more precious the need for cleanliness, and in particular for hand washing before any contact with water becomes imperative. Where water is very scarce this precautionary behaviour is rarely practiced and as a result stomach upsets, and worse, are part of the daily expectations, which significantly lower enjoyment of life and eventually shorten it. Prevention of these problems is quite possible but it needs education and discipline.

Education concerning water consumption and hygiene needs to begin with the very young at home, and should be reinforced by continual reminders in all school curricula, beginning in the first days of school attendance.

Any form of water resource development causes changes in natural conditions. Many of these changes offer opportunities for multiplication of numerous disease vectors, which may have produced little or no problems under natural conditions, but with the changes could have devastating effects. An example would be development of a tube-well to raise water to the surface. When the water is temporarily held in a surface tank or reservoir it provides opportunity for breeding of mosquitoes and flies. These opportunities were not available when the water was stored only in the aquifer. In regions where malaria, dengue fever or similar insect transmitted diseases are endemic, storage of water on the surface needs to be accompanied by precautionary measures to prevent the surface water becoming a breeding site for these disease transmitters.

In the tropics, almost all water resources development tends to increase the opportunities for some type of undesirable, and in many cases deadly, disease vector. This means that an integral part of any tropical water resource development plan, particularly in areas of water scarcity, needs to be an overt, up-front plan to prevent any increase in these preventable diseases. This means that planners must investigate what diseases could possibly increase with the development and then implement measures for their prevention. In most cases this will mean changing the method of implementation of the scheme and probably raise the cost of the project. But with innovative ideas the changes and extra costs need not be large. Failure to do this results in people's lives being changed for the better by increased availability of water, but for the worse by increased morbidity. In some earlier developments the increase in disease and shortening of life expectancy has been (and continues to be) so large that even now it would probably be better if the developments were abandoned. Examples are to be found in power production reservoirs, and in many irrigation developments in regions where river blindness and schistosomiasis are endemic.

The more common preventable insect transmitted diseases resulting from water resources development, mainly in the tropics, are malaria, dengue, encephalitis, river blindness, and schistosomiasis. All of these can be kept in check by a combination of biological/entomological understanding and engineering works and management. It is beyond the scope of this book to discuss preventive measures, but these are available in many other references. However it is important that planners, decision makers and

financiers include disease prevention as an integral part of any water resource development project.

5.6. Conclusion

In regions where water is scare the small local population has usually been effective in deriving the water it needs for an acceptable lifestyle. However as populations increase there is often a need to

- Make better (optimal) use of the usual water sources.
- Find more water.
- Carefully protect all the water.

Protection is needed to prevent, or at least minimise evaporation and seepage of stored water and to prevent physical, chemical and biological contamination. The principles of how to collect more water, how to make better use of what is collected and how to protect it from spoilation have been discussed in this chapter and some examples have been given of practical ways of conserving water supplies. Some of the principles involve cultural practices and beliefs, and hence change to these, requiring sensitivity and understanding, will only occur slowly. The majority of issues where change could be worthwhile involve only simple common sense and logic, and it should be possible, with some determination and will to quickly implement these anywhere.

6. Groundwater use and recharge

6.1. Introduction

Under conditions of water scarcity diverse water sources need to be developed, such as surface and groundwater, including the development of deep groundwater, reuse of wastewater, desalination, and use of other non-conventional water sources. Intensive attention needs to be directed towards water management, including demand management.

Groundwater plays an important role in alleviating water scarcity problems due to its inherent physical and storage characteristics. Aquifers have some specific characteristics that distinguish them from other water sources (Box 6.1) and make them quite unique in their usefulness. As such, the aquifers can be extremely beneficial in supplementing other sources from which there may be diminished yield due to drought and dry spells and can constitute useful strategic reserves for coping with water scarcity. However, for groundwater to play such a key role under conditions of water scarcity an increased understanding of the aquifer system is required and its operation and management would demand greater attention than under normal circumstances taking into consideration that will never be enough abundant.

BOX 6.1. Value of ground water resources in coping with water scarcity

- Groundwater may be found in areas where surface water is absent or difficult to transfer.
- In the case of temporal or seasonal scarcity of water, an aquifer can be operated as a seasonal water storage reservoir tapped during the dry season and recovered during the rainy season.
- Groundwater can be used as a supplementary source for blending with water from other non-conventional sources, and in conjunctive operation with other sources.
- Aquifers can be used for the storage and additional treatment of recycled water.
- Sediments in surface water are removed when water enters an aquifer and the quality of the water is improved.
- Aquifers often have a much larger storage capacity compared to surface reservoirs.
- In aquifers, the transport of water from the areas of recharge to the areas of extraction is natural and may involve very large distances.
- Groundwater reacts slowly to seasonal and medium term climate variations, acting as a buffer for such variations.

The main requirements for effective groundwater use under conditions of water scarcity include:

- Full assessment of the resource.
- Development of proper operational and water allocation plans.
- Awareness and consideration concerning groundwater quantity and quality protection, and enforcement of the necessary legal and institutional measures.
- Application of integrated water resources management towards securing the sustainability of the source.

In arid and semi-arid regions, where water scarcity is endemic, groundwater plays an immense role in meeting domestic and irrigation demands. In these regions massive use of groundwater has been practiced for some time now for large cities and long-established irrigated agricultural developments. Examples can be found in the South and Southwest United States, Northwest Mexico, the Mexico City, Israel and Palestine, the Arabian Peninsula, large areas of India, Pakistan and China, and more recently in Libya with the development of the Great Man-Made River tapping fossil groundwater from the desert of Southern Libya (UN, 1992). Settlements in desert areas of North Africa, the Near East and northern Asia also rely on groundwater use.

In these areas, although the value of groundwater in the development of agriculture and in meeting domestic and industrial demand has been considerable, concerns about the sustainability of groundwater production and the extent of overexploitation and "mining" are relevant. This is due to the fact that a good assessment of groundwater recharge is quite difficult and in most cases it is at best based on assumptions with large uncertainties. These concerns are more pronounced in regions suffering water scarcity and where large groundwater developments have occurred in recent times.

Groundwater is the largest source of stored fresh water and is often the only source of water in arid and semi-arid regions. Large aquifers underlie North Africa and the Arabian Peninsula. Though costly to develop, several countries could share the benefits of these aquifers, but exploitation strategies still need to be developed and agreements on abstraction are difficult to achieve. Many countries are already strongly dependent on groundwater and face severe problems of depletion since water withdrawals are already exceeding renewable yields.

Technological developments and improved understanding of groundwater hydraulics and hydrogeology of aquifers have allowed large-scale exploitation of groundwater. This however, has led to severe problems with the availability of water and the quality of groundwater in arid and semi-arid regions where natural recharge is less than the growing demand, or where the use of groundwater is the main method for coping with drought. In using groundwater for meeting temporary drought conditions or to cope with more permanent water scarcity problems, exploitation should be such that the sustainability of the system is not impaired. For this to be achieved, the groundwater reservoir characteristics need to be fully understood together with the discharge, recharge, and storage potential of the aquifer, for both renewable and non-renewable systems. This knowledge should lead to the development of a rational exploitation policy of the groundwater in storage, and the establishment of operational procedures for wells, boreholes and well fields. Management considerations such as economic, legal,

environmental, and institutional issues should also be integrated into the policies to ensure the sustainability of the groundwater resource.

6.2. Major aquifers and well fields

6.2.1. Groundwater reservoir characteristics

The groundwater reservoirs could be igneous, metamorphic or sedimentary, depending on the origin of the geological formation. The lithology determines the type of aquifer such as sandstone, limestone or basalt, whilst its porosity determines how water is transmitted such as through intergranular spaces, fractures, channels or karstic pathways. These are further defined by their physiographic setting such as plateau, alluvial fill or fan.

The extent and conditions for natural recharge of aquifers when these are exploited, is of great importance. This is most pertinent for areas of low rainfall, such as in arid and semi-arid regions. The exploitation of aquifers has to be planned on the basis of their "safe yield" or "perennial yield" (see Box 6.2 for pertinent aquifer definitions). Evaluations have to be performed so as to know whether the aquifers contain renewable or non-renewable water. If the water is renewable, at what rate this is renewed? If the groundwater is non renewable it is said that the aquifer contains "fossil" water, as appears to be the case for the Saharan aquifers tapped by the Great Man-Made River project in Libya (Margat and Saad, 1982; Otchet, 2000).

BOX 6.2. Some pertinent aquifer definitions

- ***Porosity*** is the ratio of the volume of voids to the volume of aquifer; it depends on many factors such as the cementation of the pores, the fracturing, the packing of the grains, their shape, size and their arrangement.
- The ***effective porosity*** or ***specific yield*** or ***storage coefficient*** of an aquifer refer to the amount of water that can be drained by gravity and is expressed as a percentage.
- The ***hydraulic conductivity*** or ***permeability*** is the physical property of an aquifer to transmit water and it is expressed in terms of velocity; it is related to the effective porosity.
- ***Transmissivity*** of an aquifer is the average permeability times the saturated thickness of an aquifer.
- Aquifer ***pumping test*** is the controlled pumping of a well for a specified time during which the rate of pumping and the drop of the water level during and the recovery after ceasing of pumping are monitored; numerous techniques for evaluation of pumping test results for estimation of permeability and specific yield are available in the literature.
- ***Safe yield*** of an aquifer can be defined as the water that can be abstracted permanently from an aquifer without undesirable results.
- ***Perennial yield*** is the flow of water that can be abstracted from a given aquifer without producing results which lead to an adverse situation.
- ***Fossil water*** is the groundwater that entered the aquifer as recharge in past geologic periods, probably under different climatic conditions, and is not renewable.

The porosity of an aquifer determines the storage and to some extent the release of

groundwater by an aquifer. Of greater importance is the effective porosity or specific yield of an aquifer since this controls the quantity of water that can be released by an aquifer. Another important physical parameter of an aquifer, which is related to the effective porosity, is the hydraulic conductivity or permeability, indicating how easily the water can be transmitted through the aquifer. Both physical properties can be evaluated in the laboratory using undisturbed aquifer samples or by the analysis of pumping tests on wells or boreholes (Box 6.2).

The groundwater storage and exploitation potential of an aquifer is not controlled solely by the lithological conditions. The setting of the aquifer, its structure and geometry should be such as to retain the water and make it available for exploitation. Thus, the dimensions and thickness, the stratigraphy or variation of lithologic units, both vertically and laterally, and the geologic and hydrologic boundaries, together with the effective porosity determine the storage and water bearing capacity of an aquifer.

The hydraulic factors associated with the occurrence of groundwater in aquifers and which affect use of the water are:

- The quantities of water available for natural or artificial recharge (climate, abundance of recharge, infiltration areas).
- The hydrogeological properties, related to the movement of groundwater (hydraulic conductivity, transmissivity, specific yield, storage coefficient, as defined in Box 6.2).
- The hydrological boundaries of the aquifer (coast, contact with waters of inferior quality, contact with a stream or lake).

Depending on whether an aquifer forms a water-table under atmospheric pressure, or it is surrounded by strata of markedly less permeability, the aquifer is called an "unconfined, water-table, or a phreatic aquifer" in the first case, or "confined or artesian aquifer" in the latter case.

The use that is made of the aquifer, and the quantities of water that may be available in the future, depend on hydro-meteorological factors such as the rainfall, evapotranspiration, and runoff, and on the ability of the aquifer to be recharged. Recharge relates to the infiltration and percolation characteristics of the unsaturated zone and on the distance to the saturated zone. Floodwaters and runoff waters, especially in arid regions, are only partly available for recharge since, usually, their occurrence is brief and there is insufficient opportunity for them to infiltrate to the aquifer.

The chemical quality of groundwater is related to the water bearing materials of the aquifer and the amount of soluble substances they contain. Furthermore, the duration of contact of the groundwater with the lithology of the aquifer influences the concentration of dissolved solids. In coastal aquifers, quality may be affected by sea intrusion, while point and non-point source pollutants can affect phreatic groundwater.

In arid and semi-arid areas, high evapotranspiration is the main cause of increase of salt concentrations in the unsaturated zone. This salt may be transported by water percolating to the aquifer. Deep aquifers often have a high concentration of dissolved solids whilst shallow systems may have low salt content when the latter receive more continuous contributions of recharge from rainfall and surface run-off, replacing volumes extracted or

discharging from the aquifer.

The exploitation of a phreatic aquifer and the increased local use of groundwater for irrigation may affect the quality of the groundwater, especially in areas of high evapotranspiration, due to the accumulation of salts at the surface and their subsequent leaching into the aquifer. Fertilizers and pesticides used in agricultural activities also affect the quality of the local groundwater when proper crop management and good agricultural practices are not adopted. Similarly, pollutants from industrial and urban areas, including heavy metals and organic substances, can produce point source contamination of aquifers when raw wastewater percolates to the groundwater.

The sustainable aquifers are those that receive recharge mainly from surface water, rainfall, streams and lakes in excess of their exploitation. This recharge could be continuous or temporary and intermittent depending on the source of supply.

6.2.2. Discharge, recharge and storage of aquifers

The outflow from an aquifer is discharged through springs, through subsurface flow into the sea, lakes, surface streams or other aquifer systems, rises into surface depressions when the water table is high, and passes into the atmosphere by evaporation and evapotranspiration. Groundwater contributes to the surface flow of streams and is the main contributor to base-flow and to dry-weather flow. Wells and boreholes, drains, quanats and similar, are artificial means for extracting groundwater. In exploited aquifers, they usually account for most of the discharge.

The recharge, which is the downward movement of water, is controlled by the supply of water infiltrating, the vertical permeability between the ground surface and the water table, and the depth to the water table. Subsurface flow originating in upland areas may add to the aquifer recharge. Because the residence time of groundwater within the aquifer is normally very large, periods of drought can be accommodated by an aquifer whereas for surface resources the impact is almost immediate.

The term “sustainability” used in reference to groundwater resources means the use of these resources in such quantities and under such conditions that would allow their renewal at a rate equal to their use. Theoretically, all water resources are renewable. The rate of renewal though, differs for the various types of aquifers. This renewal may occur within periods as short as one year in the case of a shallow minor phreatic aquifer in areas where there is rainfall, to many years as in the case of deep artesian aquifers. In the case of fossil water as found underneath the Sahara and the Arabian Peninsula, this could only be measured in geologic time. Age-dating techniques for the water in these large groundwater reservoirs show that these ground waters infiltrated during the ice age (30000 years ago). Thus one should distinguish between renewable and non-renewable groundwater resources.

Sustainability thus is a quantitative term and has the meaning of non-depletion of the reserves within the life span of water-works, say 40 to 50 years, rather than geologic times. In this respect the concept of “safe yield” of an aquifer needs to be applied. This defines the quantities of ground water that can be used which will not create any undesirable results (Box 6.2). Undesirable results could be the lowering of the water table to depths that would be too large for economic pumping, or the deterioration of the groundwater quality (as discussed in section 6.4). However, well planned ‘groundwater mining” is possible under

very specific conditions, and may be economically and socially acceptable. The term groundwater mining is used when the conscious and planned abstraction rate greatly exceeds aquifer recharge (UN, 1992).

The development of groundwater reserves depends on the special climatic conditions in an area, the water balance, the spatial distribution of precipitation and the long-term recharge. The groundwater reserves are also subjected to temporal and spatial variations that may vary on an annual or inter-annual basis. This particularity of ground water, as opposed to other minerals, plays a decisive role in its exploitation since withdrawal should not exceed the aquifer annual or inter-annual recharge. The opposite practice, such as an extended over-exploitation, would lead to the depletion of reserves and the drying up of major parts of the aquifer and its springs. This may result in irreparable damage of the aquifer system, either directly or indirectly, by drawing in water of inferior quality such as seawater as is the case of coastal aquifers, or the compaction of the aquifer granular texture, leading to land subsidence, as discussed further in Section 6.4. An outline of the types of groundwater reserves is given in Box 6.3.

The rational development and management of water resources needs to be based on long-term planning and advanced understanding of their quantitative and qualitative temporal and spatial variations, both at a national scale and to the scale of the individual hydrologic catchment and aquifer.

BOX 6.3. Types of groundwater reserves and their exploitation

- Reserves in ***live storage*** which are naturally discharged and could be exploited by pumping.
- Reserves in ***dead storage*** which are below the level of natural discharge and which could be exploited only after the live storage is exhausted.
- ***Local reserves*** that are pumped by a well or a number of wells and their pumping creates a local cone of depression.
- Reserves in ***irreversible storage*** whose pumping leads to a permanent consolidation of the aquifer and loss of water storage space, leading to land subsidence.

On the other hand, the exploitation of non-renewable aquifer systems does not differ from any other mining operation and any such policy should be carefully considered and evaluated on its own merits. Mining of groundwater might be acceptable if environmental values are not compromised and the rights of future generations are duly considered. Such a policy has to be carefully examined beforehand so as not to jeopardize the long term interests of the community and should focus on:

- Economically feasible capital investment, the local and community present and future costs and benefits due to the groundwater development.
- The foreseeable consequences arising from the progressive reduction in the availability of water, including ecological impacts.
- Equity considerations with respect to future generations.

When tapping an aquifer, the pumping schedule and quantities available largely depend on the groundwater in storage, both in terms of the type of reserves (Box 6.3) and the yield capacity of the aquifer (Box 6.4). For an idealized aquifer, in the long run, inflow

and outflow must balance.

BOX 6.4. The yield capacity potential of groundwater

- ***Mining yield*** which is the quantity extracted in excess of the recharge and which leads to the depletion of the aquifer.
- ***Perennial yield*** that is the extraction that is carried out under specified conditions and which does not create any undesirable repercussions on the groundwater reserves.
- ***Deferred perennial yield*** that consists of two different pumping yields. The starting yield is greater than the rate of the perennial yield and results in the depression of the water level. This provides water at lower cost without any detrimental effects on the aquifer. In fact this may reduce initial losses that occur at high water-table conditions such as by evapotranspiration, or subterranean flow to the sea. When the water level is lowered to a predetermined level, then the rate of abstraction is adjusted to the rate of the perennial yield.
- ***Maximum perennial yield***. For this to be accomplished there is need for maximizing the recharge potential, and the aquifer must be treated as one unit. It assumes that surface water is conjunctively used with the operation of the aquifer, and that there is a rational distribution of water demand.
- ***Sustained yield***. This is the maximum extraction rate that could be sustained by the natural recharge, irrespective of any short-term variations of recharge.
- ***Optimal yield***. This is related not only to the safe yield of the aquifer but also to the optimization of the operation and management of the aquifer and includes conjunctive use aspects where these can be applied, and artificial recharge.

A groundwater system holds a certain amount of water in storage. The storage - annual discharge ratio of an aquifer, in the dimension of years is usually quite high compared to the same ratio of a river, where it is usually very small. This feature makes groundwater very attractive in the case of droughts and temporary water shortage conditions.

6.2.3. Exploitation of groundwater storage

The exploitation of the groundwater storage should be a gradual process, starting from an investigation of the aquifer and its characteristics, followed by an evaluation of its potential, and ending with the design and operation of the wells and well-fields. Normally, an aquifer is the first source to be developed by farmers and other private individuals. This usually occurs well before any major water distribution scheme is put into operation because of the ease of access and the relatively low cost of developing a groundwater source. Therefore, in practice, the investigations that are carried out for increased exploitation of an aquifer aim to assess the safe yield and additional potential of the source.

The necessary groundwater investigations required are outlined in many publications and are beyond the scope of this text. The important issue is that before a major water scheme is implemented, all the necessary investigations, surveys and data collection needed for the evaluation of the available potential should be carried out (USBR, 1985).

An exploratory drilling program, which is based on a number of other investigations, is the most direct method for gathering information about a groundwater reservoir, and

provides a basis for designing operational boreholes and well fields after pumping tests.

The location and spacing of wells and boreholes, their depths, diameters, casing and other design specifications (gravel-pack, screen size, and location of pump) have to be determined through the exploratory drilling and pumping test program. Groundwater quality considerations usually determine the type of casing and grain size of filters to be installed. The optimum design of a well field is quite a complicated process that normally requires the use of mathematical simulation models to evaluate and to minimize interference effects between the wells and to provide results to enable yield maximization.

In water scarcity regions, groundwater often constitutes the main source of water. During droughts, exploitation of large aquifers should be undertaken with care, to avoid irreparable damage to the aquifer and to the quality of the groundwater. On many occasions and in many countries the efforts made to cope with water scarcity are very much bound up with efforts made in conserving groundwater and prevention of over-exploitation.

Obviously, exploitation in excess of the natural recharge will result in the lowering of the reserves and the piezometric head surface. This in turn will have an impact on the yield of the wells and greater energy costs will be required for pumping. Depending on the hydraulic depression created, water of inferior quality may intrude the aquifer, such as seawater or inferior quality water from deeper horizons. Similarly, though depending on the texture of the aquifer material, land subsidence conditions may develop that could result in irreparable damage to the aquifer and even cause damage to properties at the ground surface (see 6.4).

The exploitable reserves of groundwater are those that correspond to the regulated reserves, or live storage. These are included between the highest and lowest water-table level of each hydrologic year and are only a fraction of the geologic reserves that are between the lowest water level mentioned above and the bottom of the aquifer. Groundwater source development under conditions of water scarcity requires careful quantification of the aquifer potential and the optimization of its use. The exploitation policy should be so formulated as to avoid depletion of the reserves beyond a predefined level that should be defined as the minimum acceptable level which would be expected to cause minimal problems. The main issues that should be considered for a groundwater exploitation policy under water scarcity are listed in Box 6.5.

BOX 6.5. Main issues for aquifer exploitation under water scarcity

- *The groundwater yield potential needs to be evaluated.*
- The exploitation policy should be designed so as to safeguard the sustainability of the aquifer.
- The distribution of wells should be optimally designed to avoid interference between the wells and the development of water level depressions due to concentrated pumping.
- Water conservation measures should be implemented, such as: less water-demanding cropping patterns, improved irrigation systems and demand management strategies.
- Schemes for rationing of water need to be established.

6.2.4. Management considerations

Managing groundwater reservoirs under the stress conditions of meeting the demand, particularly on the occasion of lack of sufficient water resources, is a very difficult task. Some of the main issues for groundwater management in water scarcity regions are listed in Box 6.6.

Commonly, in areas where there is any kind of water scarcity, including a drought, an aquifer is already being exploited. This exploitation normally goes back a long time, having developed gradually and often haphazardly and without serious regulation and control of the aquifer system. The quantities extracted and the distribution of boreholes is usually far from optimal. This results in excessive local depressions of the water table, interference of one pumping well with another, and parts of the aquifer may be sea-intruded, whilst elsewhere in the same aquifer there may be undesired losses of fresh water to the sea or to other systems.

BOX 6.6. Main issues for groundwater management in water scarcity regions

- The lack of sufficiency of water resources makes the management of groundwater reservoirs particularly difficult. Therefore, a good assessment of the demand is required.
- Normally, aquifers under water scarcity conditions are heavily exploited, and their management is often far from optimal. A good knowledge of the overall water resources in the region is necessary.
- The high competition and demand for water makes management of an aquifer for sustainable use quite difficult. Priorities for allocation among different users should therefore be clearly understood.
- Advanced knowledge of the quantitative and qualitative characteristics of the aquifer is a prerequisite for its optimal utilization.
- Contingency plans for periods of drought, when demand is higher and recharge is reduced, are imperative to cope with increased groundwater exploitation.
- Implementation of plans and measures on aquifers in water scarcity regions is more difficult than in regions with relative abundance of water resources. Therefore, appropriate institutional, legal and administrative issues are required.
- The optimal development of groundwater should be based on the rational planning of the whole aquifer and should be based on its capacity of "perennial yield".
- Induced and artificial groundwater recharge should be carried out as a supplement to natural recharge for balancing the supply with the demand.
- Aquifers in water scarcity regions may reach critically low levels quite fast during droughts. Thus, monitoring is essential.
- Economical, social and environmental issues, in addition to technical ones, are of significant importance in managing an aquifer in water scarcity regions.
- The establishment of legislative measures to protect groundwater from pollution and over-draught are of paramount importance in regions deficient of water supplies.
- An organizational framework able to develop, monitor and control the use of aquifers needs to be established.

Under drought conditions, the available groundwater reserves are often relied upon to

meet a temporary lack of water resources. Furthermore, during such periods the competition and demand for water are very high and managing an aquifer so as to meet only part of the water demand, as allowed for in the policy of sustainable use of the aquifer, is quite difficult.

The optimal utilization of a groundwater resource needs to be based on long-term planning. Advanced knowledge is needed of the likely temporal and spatial variations of the quantity and quality characteristics of the groundwater. To gain this knowledge data should be assembled on historical sequences of droughts and extended dry spells, so that related use and conservation measures can be built into the exploitation policy. The inclusion of the contingency of reduced recharge is imperative in regions facing various levels of water scarcity to demonstrate the dangers and hopefully attenuate the pressure for increased groundwater exploitation to meet the growing demand.

Under conditions of water scarcity, the gradual depletion of the reserves and the deterioration of the water quality render the decision-making and the enforcement of plans and measures to alleviate the problem more difficult than when dealing with non-limiting availability of water resources. A major part of the decision-making procedure should be devoted to the evaluation of the priorities in the use of the limited water resources so that acceptable minimum levels of supply could be provided to meet the demand.

For sensible exploitation and optimal development of the groundwater resource, a number of measures can be used such as:

- Legal measures.
- Administrative actions.
- Set up of institutional bodies responsible for the management and operation of waterworks.
- Economic incentives and penalties.

The optimal development of groundwater should be based upon the rational planning over the whole aquifer since actions on any part of the aquifer affect the whole system. The sound management of an aquifer should be based on its capacity, translated in terms of “perennial yield”, and on a number of selected targets such as meeting a prescribed demand at a specified water quality and at minimal possible cost. Operationally, the whole aquifer should be considered.

A major concern in the utilization of groundwater is to have sufficient recharge during wet years to satisfy water needs during the dry periods. This can be partially accomplished by induced recharge, by artificial groundwater recharge (see 6.5) and also by increasing the availability of storage space in the aquifer by pumping during the dry season.

The utilization of groundwater storage in arid regions should seek to smooth out the large variation of recharge that occurs from year to year, and to preserve and maximize the utilization of the limited quantities of fresh water that are normally available in a stressed environment, where water is often saline or brackish due to the high evaporation. Priority should be given to making the correct evaluation of the groundwater storage and of the quantities available for safe exploitation. Over-exploitation of groundwater in such regions leads to increased salinity. This fact makes it necessary that storage, extraction and salinity should always be jointly considered.

The groundwater quality in coastal aquifers is particularly vulnerable due to the inland propagation of the seawater-freshwater interface. Depletion of the groundwater storage due to over-pumping and a drop of the water table to levels below the mean sea–level, create favorable hydraulic conditions for seawater intrusion. The salt water moves inland in the form of a wedge below the fresh water. This is a slow process that is often only detected after the problem has already become acute. Depleting the storage to levels below the mean sea level for limited periods of time may be possible depending on the characteristics of the aquifer. This should be done with due care and with a continuous monitoring of both the water levels and the quality of the groundwater.

In managing an aquifer, issues other than technical ones, should also be considered. For example economical, legal, environmental and institutional considerations need to be taken into account. The development and maintenance cost of a groundwater reservoir is usually small as compared to other surface water resources developments. Groundwater becomes costly if the water table is drawn to large depths and the yield is reduced. Water conservation measures can become very effective if the cost of groundwater is made to match the cost of surface water from implemented schemes. The cost of artificial recharge should be included in that for the continued use of the aquifer.

In many countries, the rational management of aquifers is impeded by the legal ownership of the groundwater and existing water rights, which have developed historically, before the development of current understanding of how the system could best be operated and managed. When the concept that groundwater is public property is adopted, then administrative authority acting on behalf of the community's best interests, controls and regulates the use of groundwater resources. Under such conditions it is possible to arrive at near optimal use of an aquifer.

In countries or regions suffering from deficient water supplies, the establishment of legislative measures to protect the groundwater from pollution and over-draught is of paramount importance. However, such measures should consider the basic premise that the aquifers may not necessarily coincide with administrative or political boundaries. Groundwater is or should be a public property, and licensing should regulate its exploitation.

Developing, monitoring and controlling the use of aquifers require an organizational framework able to carry out these duties and responsibilities. The effective implementation of any groundwater policy requires a competent, well-equipped and efficient organization that can operate on the basis of the existing legislative framework. The form that the legal framework takes, whether under a unified water code or in the provision of various separate laws, decrees or regulations is of secondary importance. The same applies to the organizational setup, which will vary from country to country, from a single Authority to a State Ministry. Of importance is good coordination among all interested parties and local organizations. To be effective the institutional setup must be strong and supplied with competent and well-trained staff in such numbers as to could cope with the monitoring, studying, regulating and controlling the use of the aquifers.

6.2.5. Aquifer monitoring and control

A complete list of required data for monitoring and controlling an aquifer is difficult to

compile because of the variety of aquifers and groundwater management problems that may be encountered. The type of data and monitoring practices required would depend on the stage of the aquifer use, its development, the demand that it has to meet, the type of aquifer and its sources of recharge, the climatic conditions, and the importance of the aquifer within the other available water resources. Monitoring and data collection are required for:

- Evaluating the aquifer itself such as its lithology, geometry and hydraulic characteristics.
- Evaluating the "perennial yield" of the aquifer, thus involving climatic data and other water-balance parameters.
- Monitoring the continuous development of pumping and hydraulic conditions such as extraction, water levels and the quality of groundwater.

Monitoring the overall water-balance of the aquifer for adjusting the amount extracted is of immense importance. Groundwater level monitoring provides information on the response of the aquifer to recharge, natural discharge and extraction conditions, and allows improved decisions on new pumping schedules to be developed. Monitoring the chemical and bacterial quality enables the evaluation of the suitability of water for human consumption and for the irrigation of certain sensitive crops. It provides information on the intrusion of undesirable water of low quality, including seawater, into the aquifer, and allows for the dynamic follow up of nitrates, heavy metals and organic components. These may result from the extensive use of fertilizers and pesticides, as well as from point source pollution from industry or town sewage. A basic checklist of monitoring and control data is provided (Box 6.7).

6.2.6. Maintenance of wells, pumps and other facilities

Wells, pumps, water storage, conveyance, and water control structures should be subject to periodic inspection and testing. It is common for wells and pumps to be neglected since the nature of deterioration that occurs in a well is not readily identified until the well fails.

The deterioration of a well usually develops slowly to a critical point and then accelerates rapidly to failure. If the problem is identified early on, then rehabilitation may be possible. Failure of wells may occur by encrustation and blocking of the screen area of the casing due to the chemical quality of the groundwater. Encrustation may also occur if the screen area of the casing is exposed to the atmosphere for prolonged periods. Such exposure may occur during periods of excessive pumping and lowering of the aquifer water level. Under the same conditions, the exposed inflow face of the aquifer against the well may be blocked for the same reasons. Other failures may arise by sand entering the well due to bad design. Sand entry can affect the pumping plant and the depth of the well itself. Items that should be monitored at regular intervals are the yield of the well, the static water level, the depth of the well and the sand or silt content of the pumped water.

During routine lubrication and servicing of pumping facilities, the following should be observed: an increase in sand content of the discharge, decrease in discharge, excessive heating of the motor, excessive oil consumption, excessive vibration, cracking or uneven settlement of the pump pad or foundation, and settlement or cracking of the ground and ground surface gradient around the well (USBR, 1985). Remediation measures for these problems need to be taken quickly to avoid development of other problems.

BOX 6.7. Check-list on field investigations, monitoring and control for aquifers

Field investigations:

- Developing planimetric, topographic and geologic maps.
- Field mapping of the structure, stratigraphy and lithology of the aquifer.
- Survey of wells, boreholes, springs and other aquifer extraction facilities.
- Establishment of groundwater level and quality monitoring networks.
- Location of sites for pumping tests, observation wells and piezometers.
- Logging of new drill-holes and wells.
- Performing geophysical surveys.
- Performing chemical and bacterial analysis of water samples.
- Collection of aquifer data such as type, thickness, boundaries, permeability, storativity, discharge and recharge.
- Determining groundwater and surface water relationships.

Hydrologic monitoring:

- *Recording and analyzing data on static and pumping water level in wells, yield, specific capacity and quality of groundwater*.
- *Follow-up groundwater table and piezometric levels*.
- Monitoring recharge, discharge and inflow contributing areas.
- Follow-up groundwater development and use.
- Recording weather data such as precipitation, temperature, air humidity, sunshine or radiation, wind velocity.
- Investigating special aspects in aquifer behavior and performance such as seawater intrusion, artificial recharge, and point source pollution.

Control through monitoring:

- New wells, drilling permits, pumping permits.
- Pumping by existing facilities and use of water as compared to permitted quantities.
- Use of fertilizers, pesticides and their levels of presence in groundwater samples.
- Point source pollutants from industry and urban areas.
- Application of legislation and regulations regarding the use of the aquifer.

6.3. Minor aquifers of local importance

6.3.1. Particular aspects of minor aquifers

Items listed above for consideration for major aquifers apply equally well for minor aquifers, but the importance of the problems may be ordered differently. By definition, minor aquifers are of limited extent and have much smaller reserves. Thus, the impacts on a minor aquifer of a prolonged drought, or of an increase of pumping when water demand rises, would be greater in absolute terms than those on a large aquifer, because minor aquifers are more vulnerable to increases in demand.

A minor aquifer would need far more careful management based on studies of the

aquifer and data on water level, estimates of recharge and yield potential, and aquifer performance under pumping. However the chances are that a minor aquifer would not have received such detailed attention, so information on its performance would be limited. Thus, under conditions of drought, if a minor aquifer is over-exploited, the repercussions could be quite severe. The community depending on it could early on experience scarcity of water with the shallow wells becoming dry and the flow of springs reducing. Exploitation and management issues for minor aquifers are listed in Box 6.8.

BOX 6.8. Exploitation and management issues for minor aquifers

Exploitation issues:

- Exploitation and management problems for minor aquifers could be more critical than for large aquifers. Therefore, the corresponding operation rules must be well known and accepted by the communities using those aquifers.
- Minor aquifers are more vulnerable to increased demand; similarly, they are more vulnerable to pollution and intrusion of water of inferior quality and susceptible to the side effects of over-exploitation. Rules for protection of the aquifers should be developed and well known by the users.
- Minor aquifers are more sensitive to climatic conditions. Contingency planning to cope with droughts is required.
- More careful management and control are required for minor aquifers since impacts of over-exploitation could be severe. Upper limits for rates of water removal need to be enforced as part of the operation rules.

Management issues:

- Often, the local minor aquifer is the sole reason for existence of certain communities and their continued prosperity. The involvement of the users in management is therefore essential.
- The sufficiency of minor aquifers in years of drought is of the utmost importance especially in isolated and remote areas such as small islands. The repercussions of water scarcity are more pronounced and abrupt, especially on the occurrence of drought. Contingency planning has to be implemented through appropriate participation of users.
- Good understanding of the geometry and lithological variations as well as of the aquifer characteristics is essential for development of meaningful management practices.
- Monitoring of ground water levels, water quality trends and estimates of recharge, as well as the control and monitoring of pumping, are highly important.
- A favorable water-balance needs to be maintained particularly during drought. At these times it is important to estimate, ahead of time, the quantities that could be pumped. Monitoring needs to be more carefully and frequently practiced under those conditions.
- Water balance evaluations help the development of water allocation and water conservation measures to be implemented in periods of water crisis. However, it is important to recruit the agreement and commitment of users when water conservation and saving measures and practices need to be implemented.
- Prudent management of the development and use of local minor aquifers is paramount for to the well being of the communities that depend on them.

Minor aquifers are often associated with small isolated developments of dunes and dune complexes commonly located in coastal areas, with alluvial plains and alluvial

deposits along streambeds, with buried river channel deposits, and mostly in arid zones, with piedmont or foot-hill formations such as alluvial fans. Minor aquifers often exist in islands, mainly those of volcanic origin. Small developments of any other geologic formation could similarly be termed minor aquifers.

A minor aquifer is normally an aquifer of small surface area and thus of small recharge capacity. The qualifying term "minor" does not only refer to the size of the formation, but also to the low water transmitting capacity or to the limited water reserves. The latter could be due to a combination of lithologic characteristics, recharge opportunity, geometry and morphology of the aquifer.

If the aquifer has small reserves, then the impact of increased demand would be immediate and equilibrium conditions would be disturbed with any marginal increase of extraction. On the other hand, if the aquifer has a low transmitting capacity and thus low yield potential, it is very likely that it would be a system of low permeability and small specific yield coefficient. This will result in great water level fluctuations and, in case of drought, the drop of water level will be quite large. This will have a direct impact on the yield of the wells and the flow of springs, and quite often it would quickly result in shallow wells becoming dry or in reduction of yields from boreholes. This would necessitate deepening of the wells or their relocation to a thicker part of the aquifer.

Minor aquifers discharging to the sea or to other neighboring systems will lose most of their water reserves if low recharge conditions prevail over an extended period. On the other hand minor aquifers in contact with water bodies of inferior quality stand to be intruded to a serious degree if increased demand is placed upon them and the hydraulic equilibrium is disturbed. In effect, minor aquifers are very sensitive to climatic conditions and to any extra burden of water demand that might be placed upon them. Similarly, such small systems are more vulnerable to pollution and intrusion of water of inferior quality. Localized aquifers with low storage coefficient and small sustainable yield are more susceptible to the side effects of over-exploitation, particularly when drought occurs.

6.3.2. Local importance of minor aquifers and management issues

Many communities and settlements have been established, grew and thrived on the basis of their proximity to an available supply of water. The importance of a local aquifer to some communities is that it is the sole reason for existence of that community and its continued prosperity. This is the case for many oases in desert areas.

Many settlements were established on the basis of an existing local minor aquifer. The growth of the settlement on many occasions has been controlled by the potential of such an aquifer. When demand for water increases beyond its capacity, water becomes particularly scarce. Augmentation of the water supply from alternate, perhaps distant sources is then a matter of costs and technical feasibility.

In isolated and remote areas such as small islands, the dependence of a community on a local minor aquifer for its domestic supply and irrigation requirements is total. The sufficiency of the aquifer in years of drought is of the utmost importance, which creates great concern to the authorities and the community members (Margeta, 1987).

The vulnerability of minor aquifers to deleterious effects from increased extraction or

from lower recharge during droughts is high, and communities that rely on them stand to feel the repercussions much more than others that depend on larger systems. In the latter case, the effect of an extended dry spell may not be noticed until much later or may not be felt at all if the dry period is followed by a wet season. Minor aquifers are also more vulnerable when technological developments, such as electrical pumps are introduced to replace the traditional extraction by hand or with help of animals. Then much more water can be easily pumped and it can be extracted from much larger depths. Therefore, wells that have been exploited for centuries may become dry or nearly dry in a short period causing enormous problems to populations that have traditionally been relying on them. This may also occur in shallow wells in large aquifers, but generally the consequences may not become apparent so quickly and may be remedied when the management of the aquifer is improved. For minor aquifers, over-exploitation due to use of more powerful pumping facilities may create a non-reversible situation.

Usually there is a contradiction between the importance of a local minor aquifer and the control and monitoring of its performance for allowing the necessary management actions to be taken. For communities depending on minor aquifers, the control of the use of the aquifer usually develops naturally and any new or excessive use of water is usually a matter of conflict for discussion among the members of the community. For larger communities, local or regional government usually places high interest on the management of local aquifers, reflecting their importance for the well being of the community.

Good understanding of the geometry and lithologic variations as well as of the aquifer characteristics is essential for meaningful management practice. Monitoring of ground water levels, water quality trends and control of pumping, together with estimation of recharge are quite important. A favorable water balance needs to be maintained, together with evaluations of the quantities that could be pumped in periods of drought. These evaluations will help the development of water allocation and water conservation measures to be implemented during periods of water crisis. Prudent management of local minor aquifers for their protection and use is paramount for to the well being of the communities that depend on them.

6.4. Environmental, economic and social impacts of aquifer over-exploitation

6.4.1. General

The use of groundwater and the depletion of groundwater storage both induce changes in the hydrological system. Disturbance of the equilibrium conditions and drawing down of the water-table causes changes in the rate and direction of groundwater flow, and may induce invasion by inferior quality water to replace the depleted reserves. Lowering of the groundwater levels may also result in spring and river flow diminution, wetland surface reduction, changes in natural vegetation and fauna and reduction of biodiversity.

The vulnerability of groundwater areas to adverse impacts of drought or to extended periods of man-made water shortage varies. Some aquifers are more vulnerable than others and, as a consequence, some communities are more vulnerable to the impacts of droughts and man-made water scarcity: excessive demand placed on an aquifer in excess of its safe

yield for a lengthy period could result in a number of serious environmental impacts (Box 6.9). These impacts need to be anticipated so that proper management of the groundwater reservoir and remedial actions are taken in time and proper pumping regimes are established.

The impact of drought or of an extended period of man-made water shortage on groundwater may vary from place to place within a country. Impacts could be highly localized because rainfall is characteristically variable in low rainfall areas. The geology and type of aquifer contribute to differing regional experiences. Groundwater drought is more a problem of access to water than absolute water scarcity.

BOX 6.9. Main environmental impacts due to aquifer over-exploitation

- Lowering of the groundwater level.
- Increased energy consumption.
- Reduction of well yield.
- Depletion of spring discharges.
- Reduction of stream base-flows.
- Drying of wetlands.
- Disturbance of natural vegetation and fauna, so affecting biodiversity.
- Degradation of groundwater quality.
- Seawater intrusion in coastal aquifers.
- Land surface changes due to subsidence.
- Changes in landscapes where water used to support the natural ecosystems.

Aquifers in arid areas depend on the occasional storm and flood events that may occur, so their development and use should be quite prudent since their sustainable operation is often questionable. The sustainability of groundwater resources in the arid zone is a serious long-term concern and continuous monitoring and evaluation should guide the management of these aquifers.

In certain arid and hyper-arid regions groundwater is tapped from aquifers that contain fossil water. A good example is that of northern Africa and Arabian aquifers, referred to above. A vast amount of the non-renewable or fossil groundwater, stored over geologic time, is trapped in the Palaeozoic to Mesozoic-Neogene (Nubian) sandstones that underlie wide areas of the Arabian Peninsula and the eastern Sahara desert in Saudi Arabia, Jordan, Egypt, and Libya. The dominance and importance of this resource is paramount in the water-resource planning and strategy in many countries, especially Egypt, Libya, Saudi Arabia, Kuwait, Qatar, and Bahrain. In the arid environment of Libya, rainfall and surface runoff have no direct practical importance. However huge amounts of fossil groundwater are stored in the Nubian sandstones that underlie wide areas of the Libyan Desert. Groundwater development and/or mining of the Nubian sandstones in the inland desert depressions, named the "Great Man-Made River project," are now seen as the key to the nation's development strategy. Tapping these fossil aquifers is associated with many problems beyond the huge investments involved and their sustainability. For example salt accumulations in surface soil layers and/or underlying aquifers, which is a typical and difficult problem for irrigation with groundwater in the arid region, cannot be neglected in

any long-term development project. In Saudi Arabia this has already caused a substantial depletion of non-renewable groundwater resources. Non-renewable or fossil groundwater resources should be carefully managed and saved as a strategic reserve for emergency or short-term use.

As discussed in Chapter 2, both desertification and water shortage is, to a large extent, the result of human intervention and the associated excessive rate of exploitation of water resources. The control of desertification relies on the sustainability of agricultural land. This in turn depends directly on the availability of water resources. The pressure exerted on the available water resources, both surface and groundwater, as related to the total renewable water resource, provides an indication of the sustainability of agricultural land. If the exploitation rate is unfavorable, which is common under conditions of water scarcity, the actual use of the resource will lead to the exhaustion of available supplies and necessitate use of water of marginal quality. It also leads to contamination of water sources by sea intrusion or contamination by water bodies of inferior quality. Similarly, the lack of sufficient water resources also leads to increased pollution of the available ones. In the same way, the non-sustainable use of water, such as over-exploitation of groundwater and draught of fossil water, may lead to unsustainable land use. Use of water of inferior quality leads to soil salinisation, which in turn renders the soils unsuitable for agriculture. The land is then abandoned and prone to erosion and increased desertification.

Water shortage could easily result from groundwater mismanagement, even in regions where shortages could have been avoided and a balance between supply and demand could be achieved. Groundwater abuse and misuse in water scarcity regions has far reaching environmental and economic consequences and comprehension of this is quite crucial in coping under conditions of limited water availability. Effective water resources management is thus essential in maintaining a balance between supply and demand within the renewable water resources potential of a region, to avoid human-induced water shortages.

6.4.2. Ground water levels

A combination of factors, including land use, technology (well, borehole, pumping plant), geology, hydrology, hydrogeology, and demography conspire to create problem areas. Simple case studies may refer to the lowering of groundwater levels below shallow wells, leaving them dry, or to the reduction of recharge due to building of a new dam upstream of an aquifer recharge area. Other examples refer to concentration of pumping near the coast creating local upcoming and seawater intrusion. Yet others refer to groundwater level drop due to increased pumping, caused by the sudden expansion of population at certain locations in response to tourism development or work opportunity. The examples indicate that vulnerability varies over space and time and it relates to the ability of users and communities to access alternative water sources and develop new water supply schemes.

Groundwater level fluctuations monitored over a large span of time reveal information on the groundwater flow regime and water balance of aquifers. More particularly they allow the following type of conclusions to be made:

- A groundwater level fluctuation about a steady mean value suggests a situation of water balance normally associated with steady hydrologic conditions.

- The fall of the mean groundwater level when accompanied by a steady reduction of the range of the annual fluctuation, suggests a diminishing natural recharge, something which could be attributed to a prolonged drought, urbanization (reduction of recharge areas) or the commitment of surface flows into surface reservoirs.
- The fall of the mean groundwater level when accompanied by an increase of the range of the annual fluctuation, suggests increasing groundwater extraction.
- A steady recovery of the groundwater level could be due to return flow from irrigation, or leakage from wastewater.

In aquifers experiencing over-exploitation, the groundwater levels fall causing depletion of groundwater reserves, a reduction of transmissivity in water-table aquifers, and a reduction of the yield and specific yield of wells. This effect is more pronounced in heterogeneous and fractured rock aquifers. Under such situations, where water levels fall below the depth of springs and shallow wells, these sources become dry or may not be viable during a prolonged water scarcity episode. In such an event, wells may have to be deepened, provided the aquifer extends to greater depths. Furthermore, the existing pumping equipment may need to be replaced if the new depths are beyond their working performance range. Improper maintenance of wells and of the pumping machinery may compound the problem of water inadequacy, especially under conditions of falling water levels (see section 6.2.6).

6.4.3. Water quality deterioration

Over-exploitation of aquifers that are in contact with the sea or other water bodies of inferior quality may result in the deterioration of the aquifer's water quality.

A drop of the water table below the level of the sea disturbs the existing equilibrium and seawater propagates inland rendering the groundwater useless for irrigation or domestic supplies. This process takes some time. Therefore, it is not unusual to lower the water table to levels below the sea level for limited periods of time, varying from months to years, depending on the local hydrogeological conditions. This is common in arid and semi-arid regions where major recharge events do not occur annually, but at irregular time intervals. However continued over-exploitation, may create irreversible conditions for the quality of the ground water.

In the same way, if groundwater of inferior quality exists in the same area as an exploited aquifer may invade if the aquifer is over-used. Wells and groundwater galleries may have to be abandoned if invaded by water of inferior quality unless some form of treatment is introduced before water use. Repeated use of low quality water may seriously damage agricultural soil, vegetation, and animal biodiversity and may cause human health problems.

Over-exploitation of aquifers during periods of water scarcity causes much steeper hydraulic gradients towards wells. These conditions favor increased groundwater contamination from the ground surface especially if the area is agriculturally developed. This quality deterioration could become quite serious and affect the use of groundwater for drinking purposes. The pollutants that cause the most concern are nitrates and to a lesser extent pesticides, heavy metals and organic compounds.

Outbreaks of disease may occur as people use unprotected, traditional sources or sources invaded by inferior quality groundwater. In general, scarcity of water causes the search for and development of new sources of water and as the scarcity worsens so does the quality of water considered acceptable for use.

6.4.4. Sea water intrusion

Although sea intrusion falls under the heading of ground water quality deterioration, the extent of this problem is so important for over-exploited coastal aquifers that it merits a separate discussion.

Some 60 percent of the world population lives within 60 km of the coast. This concentration of human settlements, associated with increasing agricultural and industrial activities along the coast, exerts an excessive pressure on the coastal aquifers. Some seawater intrusion and deterioration of the water quality is inevitable whenever groundwater is abstracted from coastal aquifers. This may become a serious problem especially under water scarcity conditions.

Seawater intrusion is a slow process and considerable time may pass from the onset of the phenomenon until increased salt is noticed in water wells. For this reason, seawater propagation inland has to be adequately understood and monitoring programs need to be established to detect it early enough, so that the situation may be controlled, and if possible reversed.

In aquifers that are in contact with the sea, there is an interface between the fresh water, whose relative density is 1.0 kg l^{-1}, and the seawater, which has a relative density of about 1.025 kg l^{-1}. Because of this difference in density, the seawater is below the fresh water on the landward side of the coast. The fresh and saline water are miscible, therefore this interface is not sharp but rather a mixing zone exists between the two water bodies. The extent of the mixing zone depends on the hydrodynamics of the system and on the degree of interference to the natural equilibrium conditions, usually caused by exploitation.

Groundwater levels and the depth to the saline wedge are related by the "Badon-Herzberg" equation that is based on a simple application of hydrostatics. This relationship, arising from the relative densities of fresh and saline water, suggests that the depth from the mean sea level to the saline part of the interface, under steady conditions, is about 40 times the height of the water table above mean sea level. Thus, a drop of one meter of the water table would theoretically result in a rise of the saline water by 40 meters. This relationship applies well when the system is under steady conditions and when the dispersion zone is very small compared to the total saturated thickness. The problem becomes quite complex under unsteady conditions and for aquifers with a small thickness.

Sea intrusion problems may occur both on a large scale, such as along the whole front of the aquifer with the coastal line, or on a local or small scale, such as for a well or a well field relatively close to the coast. Large-scale propagation of the interface occurs in response to large groundwater abstraction and de-watering of the fresh water from the aquifer. This over-exploitation that induces the sea intrusion endangers the continued use of the aquifer and the water supply. Local or small scale sea intrusion is caused by individual wells or well-fields near the coast, the over-pumping of which causes an up-coning and local deformation of the interface resulting in the gradual increase in salt content of the

pumped groundwater.

In coastal aquifers, the hydraulic gradient under natural conditions is towards the sea so that there is a natural outflow of fresh groundwater. Very often, and especially where the topographic elevation is low, which is usual near the coast, this hydraulic gradient is small, and therefore, a little groundwater extraction may be enough to disturb the natural system, reverse the hydraulic gradient, and cause sea-water invasion. The problem becomes quite serious when the coastal aquifer is over-used and, more so, when there is a concentration of wells near the coast. Concentration of wells near the coast is common since normally at this location the aquifer is thickest, the pumping head is the least, the yields are largest and this is where settlements are located.

Appropriate management approaches to prevent and control seawater intrusion need to be considered as a priority for sustainable management of coastal groundwater resources. This becomes imperative in regions experiencing water scarcity and where heavy exploitation of groundwater is carried out. The difficult dilemma though, is to have to control and reduce extraction at a time when t the alternative water resources are limited and the demand is high.

Among the measures that need to be taken are to reduce the pumping and in some cases, to change the location of the wells away from the coast, adopting a more optimal distribution of wells in the aquifer. These are difficult measures to implement due to social, legal and economic reasons. As a result, the situation often becomes worse due to delays in obtaining agreements before measures can be implemented. Other approaches include artificial groundwater recharge, which can be used to establish a high water table near the coastline (see section 6.5).

6.4.5. Land subsidence and land collapse

Intensive groundwater use, resulting in depletion of aquifer storage and lowering of the water table, under certain aquifer conditions, may cause land subsidence and the development of new sinkholes in the case of carbonate aquifers.

Land subsidence occurs in areas of serious lowering of the water table where the lithology of the underlying aquifer consists of poorly compacted sands and clays. Subsidence is associated with de-watering and consolidation of clays. The dynamics of land subsidence caused by a declining water table depend on the intensity of groundwater abstraction, the extent of decline of the water table, the geological structure of the aquifer, the soil compressibility properties and the thickness of the aquifer.

Groundwater withdrawal has little effect on aquifers consisting of solid and coherent rocks or unconsolidated gravel beds and sandy rocks that are non-compressible. In contrast, clayey soils, silts and peat have the largest susceptibility to compression and consolidation. Similarly, aquifers exhibiting inter-bedding of quite compressible clayey rocks with sand and gravel or other permeable formations, are liable to land subsidence when subjected to substantial groundwater withdrawals. The permeable formations intensify and accelerate the process of soil draining and water depletion, thus leading to the compaction of the clayey component.

Intensive groundwater abstraction from calcareous aquifers may also cause another

similar problem, that of land collapse. This phenomenon is due to karstic processes. Sinkhole formation, which is the collapse of land resembling a funnel, is a natural problem in areas underlain by calcareous rocks, such as limestone and gypsum. The rock material is dissolved by the movement of groundwater, which action is seriously intensified when excessive lowering of the water table occurs.

The intensive use of groundwater and the lowering of the water table re-activate the karstification phenomenon of calcareous rocks. The activation of karstic processes proceeds with the restoration of older karstic features and the creation of new ones. Intensive groundwater use in such an area changes the natural and static hydrodynamic conditions and the directions of flow of groundwater. The re-activation is caused by the introduction of "fresh" water unsaturated in calcium carbonate, which dissolves the calcium carbonate of the rock material, whether limestone or gypsum. At the same time, the mechanical action by the incoming water adds to the problem. As a consequence, new recharge areas, in terms of sinkholes and caving, are developed, and previous discharge points may become feed locations. The activation of karstic processes poses serious dangers to surface structures and new wells and pumping patterns need to be planned only after all the repercussions are studied in such areas.

6.4.6. Stream base-flow reduction, drying of wetlands and landscape changes

Excessive groundwater abstraction and lowering of the reserves and the water table may have a major impact on river flow, and particularly on the base-flow, which generally constitutes the natural discharge of the aquifer. This may come about by the reduction of the flow of springs and by modification of the hydraulic conditions controlling the stream-aquifer interactions due to the reduction of the groundwater levels.

Water scarcity affects both surface and groundwater because of the intrinsic relationship between them, especially in the case of an unconfined aquifer, and any disturbance to the existing equilibrium of one brings about changes and modifications to the regime of the other.

Increased groundwater use from an aquifer should be studied in connection with the surface runoff of the same catchment area and the effect of the development of the one source on the other should be carefully assessed. Normally, a conjunctive use approach should enable maximization of water resources utilization, but the side effects on the general environment due to excessive groundwater use should be considered.

The decrease of the stream base-flow due to a reduced contribution from groundwater has repercussions on downstream users and water impoundment works, as well as on the continued existence of wetlands, and riparian vegetation in the low lands of the river basin. The quality of the surface water resource is also bound to deteriorate due to the absence of the blending effect provided when stream flow discharges are higher during the low flow periods.

The presence of wetlands is normally associated with the presence of surface stream base-flow, or due to a high water table associated with a local lowland area. De-watering of the local aquifer causes a lowering of the water table and a reduction of stream base-flow resulting in the drying of wetlands.

Shallow water table aquifers supply water by capillarity to the natural vegetation, or to agricultural crops. A drop of the water table will result in vegetation withering and drying up. This impact is more pronounced in the case of wetlands and riparian vegetation belts. Some local endemic species may be affected or may even disappear. The fauna associated with the affected vegetation and wetlands suffer equally. These include migratory and non-migratory birds which use the affected areas for breeding. Soil fauna and flora is also impacted. Overall, biodiversity may be affected to a large extent.

The same applies to the general landscape that may equally be affected by excessive groundwater use and depletion in areas of unconfined aquifers. Natural ecosystems that produce specific or unique green landscapes in an arid territory, which depends on shallow water tables, wither and die when access to capillary soil water is denied by the lowering of the local water table.

6.4.7. Economic and social impacts

The quest for water in areas of water scarcity or under a prolonged drought episode results in intensive groundwater extraction. This increased groundwater pumping entails and is associated with many undesirable environmental impacts that in turn lead to serious economic consequences.

Capital investment in well construction and pumping plant may be totally lost if the well runs dry, unless it can be deepened. Larger capital investment will be required for wells of increasing depth. Additional costs will be incurred where yields decrease and escalating recurrent costs will be associated with pumping from ever-greater depths. The same apply in the case of intrusion of water of inferior quality with the consequent abandoning of wells.

Great economic and social costs are associated with the abandoning of wells, particularly in minor aquifers, when they become dry or their use becomes prohibitive due to deterioration of water quality. Costs refer to the need to develop other water sources and to changes in the economic activities which were relying on the use of that groundwater. Large economic costs are also associated with measures to re-establish equilibrium where the unbalanced exploitation of aquifers led to such deterioration. Social costs are also associated with the restrictions that have to be imposed on small farmers, who are often poor, when access to irrigation water has to be limited. The abandonment of the area by populations migrating to locations where they expect to have better life conditions constitutes a major impact of over-use of groundwater. When springs dry out in rural areas, rural populations are obliged to increase their time investment in collecting water from distant locations, often in conflict with other villages that were previously using that source.

Economic and social costs are also very high when the over-use of aquifers, coupled with uncontrolled land uses, facilitates the contamination of aquifers, so making them inappropriate for domestic and other high quality-requirement uses. Then quite costly water treatment to free water from nitrates, heavy metals and other substances have to be practiced, leading to higher costs for the water delivered to users. Social costs are particularly evident when poor urban and peri-urban populations need to search for other water sources. In the case of degraded surface wells and springs in rural areas, villagers need to search for new sources at some distance, demanding additional time and increasing

competition and sometimes conflicts with others.

Large economic and social costs also accrue from land subsidence produced by lowering of water tables. Roads, houses and other infrastructures may be highly affected when uneven ground conditions occur due to differential land subsidence. Costs are associated with the repair of houses and buildings, roads and hydraulic infrastructures. Surface water conduits may have to be totally rebuilt. Additionally, economic activities may be very much disturbed causing serious problems for poor families.

The environmental costs of wetland diminution and landscape change are high but very difficult to assess in economic terms. Impacts are more evident when rare vegetation and animal species are endangered, when nesting conditions for migratory birds are affected, or when the "green" landscape constitutes an almost unique ecosystem in an arid or semi-arid zone. Economic consequences are easier to be evaluated when human populations make use of such oases or natural green areas. The environmental impact of any groundwater management plan on wetlands and riparian ecosystems depending on groundwater should be taken into account. Moreover, the added benefits from the recovery of such ecosystems, together with the economic and social impacts as referred above, should be considered when performing any costs-benefit analysis on the improvement of the groundwater quantity and quality in any deteriorated area.

6.5. Artificial recharge

6.5.1. General

Under scarcity conditions, withdrawals during the dry season often by far exceed the safe yield of aquifers, resulting in the depletion of the reserves and occasionally, allowing water of inferior quality to intrude into the aquifers. As already analyzed, flash floods during the rainy season may not have sufficient opportunity to infiltrate the aquifers with the result that much needed water may not be utilized.

Among a number of management interventions that could help improve the situation is that of artificial groundwater recharge. This aims to increase the groundwater potential by artificially inducing increased quantities of surface water to infiltrate the ground and be later available at times of need. It could also help control or even reverse the sea-intrusion propagation in an aquifer caused by long-term or seasonal excessive pumping. This can be accomplished by creating positive groundwater levels through artificial groundwater recharge at selected strategic points in the aquifer. Furthermore, it could be used to improve the quality of pre-treated sewage water, and store it for subsequent development and reuse. In areas where there is seasonal variation of stream flow availability, water can be conserved through artificial groundwater recharge in the wet season for use during the dry season. Furthermore, control and recharge of water in wet years may help reduce the impact of droughts and to some degree alleviate man induced water shortage problems.

Maintaining a head of fresh water above sea level can prevent seawater intrusion. In many such places, artificial groundwater recharge is relied upon for blocking encroachment of seawater, retarding it or even reversing its movement. In such cases the recharge schemes serve as hydraulic mechanisms to control seawater intrusion and to allow

improved management of the available groundwater reserves. Artificial groundwater recharge can be used to create a groundwater mound or ridge. A series of spreading grounds or injection wells or a combination of both could be used, depending on the geologic conditions. Such an approach has been practiced extensively on the coast of California. The location of the recharge works and of the fresh water barrier should be far enough inland so as to force the entire seawater wedge back seaward. If too close to the coast the fresh water will separate the salt wedge and force the landward part of it still further inland.

Artificial groundwater recharge schemes may also enable the disposal and storage in the aquifer of treated effluent. This is particularly advantageous during seasons when reuse requirements are minimal. The water can then be recovered for use when it is needed. An added advantage is that wastewater made to infiltrate through the soil is renovated and its quality is considerably improved through the so-called soil - aquifer- treatment (SAT), as referred in Chapter 7. This is nothing more than the "trickle filter bed" that is used in standard sewage treatment plants except that the soil in SAT is in its natural state. This filter is more extensive but is equally efficient provided that the soil bed is pervious. In the same manner, bacteria forming around the soil grains feed on the organic matter of the sewage, relieving it of its organic load. Only the upper part of the soil horizon in the unsaturated zone takes part in this process, extending from half to a few metres depth in exceptional cases.

Thus, artificial groundwater recharge may be defined as the planned activity whereby surface water from streams or reservoirs is made to infiltrate the ground, commonly at rates and in quantities many times in excess of natural recharge, providing for an increase in the yield of the resource. Reclaimed sewage water can also be considered as an additional source of water. The benefits of artificial recharge are summarized in Box 6.10.

Water resources development anywhere, and especially in areas of water scarcity, requires the consideration of all options available. Among these options is the artificial ground water recharge that has to be competitive with other alternatives. The benefits and disadvantages need to be assessed on the basis of capital investment required in works, operation and maintenance costs, aesthetic considerations, amenities, and environmental and social impacts. The augmentation of the groundwater and conservation of water in general, through artificial recharge should be compared with other conventional and non-conventional schemes.

BOX 6.10. Benefits provided by artificial groundwater recharge

- Counteraction of aquifer over-exploitation (depletion of reserves, localized excessive pumping).
- Combating seawater intrusion in coastal aquifers.
- Increased use of underground storage through the building up of reserves during wet years.
- Renovation and quality improvement of reclaimed sewage effluent.
- Improved economics compared to surface impoundment of water.
- Improved overall groundwater quality, depending on the quality of the recharge-water.

Depending on the quantities of water involved and the aquifer characteristics,

artificial groundwater recharge can achieve two important hydraulic effects. These are a rise of the piezometric level and an increase in the available volume of water in the aquifer. The extent of the rise of the piezometric level is controlled by the quantity of water infiltrated, the transmissivity of the aquifer, which controls the dispersion of the water within it, and the storage coefficient or the specific yield of the aquifer, which controls the level of rise. The volumetric effect is related to the specific yield, the transmissivity and the geometry of the aquifer. The bulk of the recharged water spreads out depending on the natural groundwater flow pattern and the rate of recharge that is being accomplished.

The basic and most important factors that need to be taken into consideration for any scheme of artificial recharge are given in Box 6.11. Aquifers that can absorb large quantities of water but do not release them quickly are best suited for artificial recharge. This implies high vertical and moderate horizontal permeability, conditions that are not frequent in nature. Carbonate karstic aquifers may accept large quantities of artificially recharged water but tend to release them very quickly, making them less suitable for this activity. Alluvial aquifers appear to be most suitable, normally being close to sources of surface water from streams, and because they usually present high infiltration capacities coupled with moderate horizontal transmitting capabilities. Most of the artificial recharge works are located on coastal alluvial aquifers mainly because these areas are heavily populated and the local aquifers are extensively exploited. Furthermore, artificial recharge works are the last schemes where excess water can be gainfully utilized before it runs off to the sea. Artificial recharge thus serves the double purpose of augmenting the reserves of water and protecting the aquifer from seawater intrusion.

BOX 6.11. Hydrogeological and groundwater factors influencing artificial groundwater recharge, and choice of scheme

- The hydrogeological conditions must be amenable to the infiltration and percolation processes associated with artificial recharge.
- The physical and mechanical properties of the pervious media (soil and aquifer) must facilitate desirable infiltration rates.
- The water-bearing deposits must be able to store the recharged water temporarily and subsequently to permit its lateral movement at acceptable rates.
- There must be an efficient means of recovering the recharged water (which is more important in the case of combating sea intrusion since a large proportion of the quantity recharged would otherwise flow to the sea).
- The hydraulic conductivity and coefficient of storage of the aquifer need to be high. These define the ability of the aquifer to allow water to infiltrate and then to disperse, and the capability of the aquifer to temporarily store the infiltrated water.
- The filtration, deposition, precipitation and absorption characteristics of the upper layers of the aquifer. These processes take place during and immediately subsequent to infiltration in the recharge basin. They tend to improve the water quality but to reduce the pore dimensions and lead to smaller infiltration rates depending on the sediments carried by the water being recharged.
- The availability of an adequate source of recharge water of suitable chemical and physical quality.
- The proposed recharge installations must be competitive to other water resource development options and be economically and environmentally sound.

The artificial recharge scheme to be selected depends on such factors as the relationship between the physical and mechanical properties of the aquifer and the desirable infiltration rates. It also depends on the effect of the aquifer material on the chemical and biological improvement of the water, the ability of the aquifer to store the recharged quantities temporarily and to permit lateral movement of the water at reasonable rates and over adequate retention times.

6.5.2. Methods of artificial recharge

The artificial groundwater recharge schemes may be classified under two broad groups:

- The indirect methods through which increased recharge is achieved by locating means of groundwater abstraction as close as possible to areas where surface water is in contact with the aquifer or areas of natural water discharge. In such cases, the natural hydraulic gradient is affected so as to cause increased recharge.
- The direct methods through which surface water is conveyed from lakes, reservoirs, waste water treatment plants or is being diverted from flowing streams to suitable areas of aquifers where it is made to infiltrate to the groundwater from basins, trenches, dry riverbeds, injection wells, pits, etc.

Indirect or induced artificial groundwater recharge consists of abstracting groundwater within a short distance from a flowing stream, lake or impoundment. The pumping lowers the piezometric surface to cause a steeper hydraulic gradient, thus inducing increased recharge. The same artificially developed conditions tend to reduce the outflow of local groundwater into streams and surface water storage. The groundwater abstraction facilities could consist of well fields, a gallery or a line of wells. Depending on the hydrogeologic parameters of the local aquifer, considerable amounts of surface water could be induced to infiltrate into the aquifer. Higher permeability favors larger quantities to be recovered through pumping wells.

The problems associated with this otherwise straightforward approach are the siltation of the river banks and channels where the increased infiltration takes place, the quality of the recovered water, which depends on the state of the surface water, and the possible need for storage facilities to hold the water recovered by pumping. A minor problem that may develop, and which has to be investigated in advance of the implementation of induced recharge, is the additional proportion of groundwater that may be abstracted over and above the induced infiltration of surface water. Excessive natural groundwater pumping may have undesirable effects on local groundwater hydraulic conditions and adversely affect other users if the piezometric head drops.

With the direct methods of recharge, better control can be exercised over both the quantity and the quality of the water. In addition, the recharge activity is performed during the periods of available surface water irrespective of whether there is a need for pumping or not. Surface water diverted from a stream or lake is transported to the selected site and introduced into the aquifer by spreading basins, injection wells or pits shafts. Direct methods have a number of advantages over indirect methods including the lesser importance of the distance to the raw water source, the opportunity to treat the raw water before recharge, less effort for clean up of the clogging of the spreading grounds, operation of the recharge scheme at will, and the opportunity for strategic location of the recharge

works on the basis of environmental, hydrogeologic and management considerations.

6.5.3. Artificial recharge by spreading

Artificial recharge by spreading is usually carried out when the aquifer extends close to the ground surface. Recharge is accomplished by spreading water over the ground surface or by conveying the raw water to basins and ditches. Use of spreading grounds is the most common method for artificial recharge. The operational efficiency of the spreading grounds depends on the following factors:

- Presence of sufficiently pervious layers between the ground surface and the aquifer.
- Enough thickness and storage capacity of the unsaturated layers above the water-table.
- Appropriate transmissivity of the aquifer horizons.
- Surface water clean enough to avoid excessive clogging.

Thus, the quantity of water that can enter the aquifer from spreading grounds depends on three basic factors:

- The infiltration rate at which the water penetrates the ground surface.
- The percolation rate, i.e. the rate at which water can move downward through the unsaturated zone until reaching the aquifer.
- The capacity for horizontal movement of water in the aquifer, which depends on the horizontal permeability and thickness of the aquifer.

The infiltration rate tends to reduce over time due to the clogging of soil pores by sediments carried in the raw water, growth of algae, colloidal swelling, soil dispersion and microbial activity. The infiltration rate may recover when adopting alternate wet and dry periods of spreading and by scraping away the clogged surface layer, among other techniques.

A spreading basin is normally constructed with a flat bottom that is covered evenly by small quantities of water. This requires the availability of large surfaces of land for meaningful size recharge works. Normally the basins are arranged so that excess water runs into the downstream basins. Retaining basins may be used for settlement of suspended sediments before water enters the spreading basins. The settling of sediments may also be assisted with the addition of coagulation agents. Intermittent operation of the spreading basins may allow the reconstitution of the major part of the initial infiltration capacity.

Variations of the spreading ground technique consist of the use of ditches that are often easier to handle and for which clogging is a lesser problem since a major part of the sediment is carried out of the ditches. Similarly, flooding dry riverbeds or relatively flat land could be an effective artificial recharge scheme with self-cleaning abilities. Another variation of this approach would be the use of the flat infiltration area for irrigated agriculture where excess water is applied to percolate downwards from the irrigation basins into recharge.

6.5.4. Artificial recharge by well injection

When the aquifer is located at some moderate depth below the ground surface, recharge

may be accomplished by introducing water through pits and shafts and, in the case of the presence of overburden of a large thickness, water can be injected through wells or boreholes which reach the aquifer. This technique is also preferred where land is scarce, when environmental reasons oppose the use of large spreading grounds, when the local hydrogeologic conditions do not favor spreading, or wells and pits are already available for use for recharge. In areas where the pervious formations are at shallow depth, recharge can be accomplished by digging pits or shafts. Abandoned gravel pits could also serve as recharge sites.

Injection wells are quite versatile in that they can be used on any type of aquifer. However, they require pre-treatment of the raw water, since these wells easily become clogged, necessitating difficult cleaning operations, or even their abandonment and drilling of new injection wells. The recharged water is directly injected into the aquifer without much opportunity for further polishing, and so the technique must be restricted to using high quality injection water. In most cases it should be of drinking quality. Even if such high quality water is used, trouble-free operations cannot be guaranteed for long periods of time.

The injected water is preferably introduced at the bottom of the well since "free fall" of water into the well entraps air bubbles that adhere to the pores of the formation restricting the intake rate. A common practice is to inject water through extraction wells. This allows cleaning of the well and restoration of the capacity for water to flow to the pump. In such a case the water is injected through the pump column and the pump.

The capacity of the wells to absorb the injected water depends on the available conveyance capacity of the surface installations and the well equipment, on whether the aquifer can laterally transmit the water, and on the extent of clogging of the borehole walls that is caused by the injection itself. Chemical and bio-chemical processes, admission of air into the aquifer's pores, accumulation of colloidal particles on the walls of the borehole and in the immediate aquifer interstices may be the cause of clogging. When the capacity of the recharge well deteriorates to below an acceptable operational level, some kind of redevelopment is necessary. This can be done by occasional back washing by pumping the same well.

6.5.5. Recharge with surface and subsurface dams

Other types of artificial recharge schemes refer to floodwater retention dams, especially on broad wadi floodplains. The purpose of these is to delay the flow of the water and provide the opportunity for recharge into the local aquifer. The structures consist usually of low dams, including earth walls and gabions built to be toppled by floods.

More permanent structures refer to recharge dams, which are proper water impoundment works across stream channels, located at sites overlying aquifers. These are equipped with proper spillways and could be used for artificial groundwater recharge at the site and to release water through outlets towards spreading grounds or other types of recharge schemes. In these cases, the recharge dams act to provide both direct recharge and sediment retention, providing clear water for recharge purposes.

In the case of narrow streams, and provided the hydrogeological conditions permit, subsurface dams could be created by a number of approaches such as slurry trenches,

cement and other chemical injection, reducing the permeability of the subsurface lithology. The excavation and construction of the subsurface impervious wall is performed during the dry season. The subsurface dams control the subsurface flow, impound it underground and provide a source for water during the season of demand.

In areas where the pervious formations are at shallow depth, recharge can be accomplished by digging pits or wells. Abandoned gravel pits could also serve as recharge sites.

6.5.6. Problems and solutions

A summary of the basic problems in performing artificial groundwater recharge, and some solutions, are listed in Box 6.12. A major problem in artificial recharge activities is the non-availability of sufficient quantities of water of acceptable quality for recharge with some degree of regularity. The recharge schemes, especially in areas of water shortage, tend to operate on a very occasional, intermittent manner, usually associated with the availability of surplus water that can be used for this purpose. This causes the recharge schemes to remain idle for long stretches of time, requiring proper maintenance before re-activation.

BOX 6.12. Problems in artificial groundwater recharge and solutions

Problems:

- Availability of water
- Quality of available water for recharge
- Regularity of water supply for recharge
- Need for maintenance after lengthy idleness of the scheme
- Reduction of infiltration capacity due to quality and suspended load of water
- Compaction of soil in recharge area during maintenance

Solutions:

- Reduction of sediments for prolonging the efficiency of the recharge scheme
- Control of biological and chemical impurities
- Absence of dissolved air and gases, which reduce the permeability of the aquifer Occasional re-development of the well through pumping for removal of bacterial growth on the walls of injection wells
- Chlorination of injected wells to reduce the bacterial growth
- Intermittent operation of recharge works for reduction of algal growth and other biological activity
- Careful cleaning and maintenance operations so as to avoid soil compaction

Another major problem that can be expected in the operation of an artificial recharge scheme is its effectiveness over a long period of operation, since, in time, a reduction of the infiltration capacity of the scheme can be expected. This depends almost entirely on the quality of the raw water and the amount of suspended sediments it contains. Thus, measures that reduce the sediment content of the water would reduce the rate of clogging and prolong the efficient use of the scheme. This condition is essential in the case of recharge through

injection wells where suspended sediments tend to clog the aquifer formation exposed within the well.

The quality of the injected water in wells is very important. Suspended solids, biological and chemical impurities, dissolved air and gases, turbulence and temperature of both the groundwater and injected water all have an effect on the life and efficiency of a well by causing clogging or corrosion of the well screen. A large amount of dissolved air in the recharge water tends to reduce the permeability of the aquifer by "air binding". The injected water should have a temperature only slightly higher than the temperature of the aquifer.

Bacterial growths also tend to develop on the walls of the injection wells and the exposed face of the aquifer. These are normally removed by occasional redevelopment of the well by pumping. Very often, chlorinating the injected water could reduce the bacterial growth but even in this case some re-development of the well by pumping is normally required. Clogging by biological activity depends on the quality of the raw water, the environmental conditions such as temperature and sunshine duration, which promote algal growth, and the type of soil at the ground surface. This problem is usually resolved by the intermittent operation of the recharge works since alternating wet and dry periods of the spreading ground helps renovate it and recover most of its recharge effectiveness.

Artificial recharge of confined aquifers can only be achieved if the confining layer is penetrated through excavation or drilling. Additionally, sufficient pressure exceeding that of the groundwater in the confined aquifer must be exerted so that water can be injected into the aquifer. Normally, artificial recharge in this type of aquifer can only be achieved through injection wells, if the hydrogeological conditions would allow.

The smaller the aquifer, the greater the impacts of artificial groundwater recharge. In a case in Cyprus at Germasogeia, artificial recharge of a streambed aquifer of 5 km length by 0.5 km width and an average depth of 50 meters, the active storage is replaced 2.5 times a year by recharge of water released from an upstream dam and by pumping of the water for domestic supply (Simmers, 1997). The quality of recharge water is very important in the whole operation so as not to deposit fine sediments on the recharge area and not to reduce the infiltration capacity.

6.5.7. Environmental impacts of artificial recharge

Groundwater abstraction lowers the water table that might lead to a number of adverse environmental effects as analyzed in Section 6.4. Such a situation becomes worse under conditions of water shortage when excessive groundwater is pumped to meet the demand. Artificial ground water recharge helps in ameliorating these adverse conditions by blocking sea intrusion, augmenting the groundwater reserves and raising the water table. The same technique may also be used for introducing wastewater of variable degrees of treatment for further quality improvement and for storage in the aquifer.

Over a prolonged period, artificial recharge may result in some degree of clogging of the soil pores. This causes a reduction of the recharge efficiency of that particular area, not only for the artificial recharge operation but also for natural recharge. However this problem is of limited spatial extent, and does not seriously affect the overall recharge capacity of the system. Removal of the deposited silt and use of soil treatments may

ameliorate the problem to a large extent. Compaction of the soil surface within the recharge area should be avoided at all times.

Adverse effects could be avoided within the spreading grounds if a regular dry and wet cycle is observed. Any growth of algae, and odors from biological growth in standing water, are controlled through drying the recharge grounds at regular intervals. Proximity of spreading grounds to population centers may cause problems, especially if the water remains stagnant for a long period of time. Operating the spreading grounds with some intermittent schedule tends to discourage breeding of mosquitoes and development of odors. Fencing and landscaping of the grounds could help suppress hazards and environmental concerns.

6.6. Conjunctive use of surface and ground water

Sound water resources development and management seeks to maximize the water resources availability at the least cost. This is even more important in arid and semi-arid climates and where droughts are quite frequent. In those regions and in areas with great fluctuation of demand, conjunctive use of surface and groundwater storage is often relied upon to offset deficits in the dry season and accommodate storage and recharge of excess water in the wet season. This is also the case for small to medium size islands, where the economic dimensions of dams is usually small, whilst the water supply demand in tourist areas increases disproportionately due to the seasonal character of tourism.

In many such regions, the water managers may have a choice of sources between surface water and groundwater. Often it is found expedient, especially with regard to increasing the reliability of yields and the economic viability, to develop both sources and use them jointly for improved performance. Such combined use would be called a conjunctive use scheme. The term conjunctive use of surface and groundwater is defined as the coordinated use of both these sources for the supply of water, as distinct from the separate development of each source without regard to the other. Conjunctive use may be enlarged to include water from desalination plants and treated wastewater. It should be emphasized that in a conjunctive use scheme, none of the water sources could meet a prescribed demand on its own but the joint use of them could satisfy it at an acceptable reliability level. This points to the difference between the concepts of conjunctive use and that of multiple resource utilization.

The ability to incorporate use of groundwater storage with surface water storage, or with water made available from other non-conventional sources (see Chapter 7), has significant importance. A small groundwater storage that can be relied upon on the occasion of a drought or during the season of increased water demand could result in a considerable increase in the reliability of the supply in satisfying a defined demand. Multiplicity in the type of sources of supply has the advantage of using the different characteristics of availability of water from each source, whether a surface water or groundwater source. Optimal switching from one source to the other may result in an increased, steadier and more reliable supply.

Multiple resource systems can rely on components with different hydrological and economic characteristics such as surface reservoirs, aquifers and/or desalination units etc.

Inherent to the advantages of these systems when conjunctive use is considered is the selection of a set of component sizes and operation rules that may lead to acceptable performance at minimal capital and operation costs.

The optimum development and management of scarce water resources is of great importance. Finding an optimal system often requires mathematical descriptions of the behavior of complex water resources systems and of their conjunctive operation. As the scarcity of water increases, so does the necessity for more wide-ranging and comprehensive methods for conjunctive use of several sources. The optimization of water usage through operating policies that not only maximize the water availability but also minimize the operating costs has far reaching effects for national development. As development moves forward water is often a constraint on further development.

The physical constraints pertaining to a water resources system consisting of a surface reservoir and an aquifer and the advantages that make the conjunctive use of its components desirable and useful are as follows:

- The demand is greater than the surface reservoir yield.
- The maximum borehole abstraction rate is less than the demand.
- The combined yield of the reservoir and the aquifer is greater than the demand.

In such a system, the aquifer is a source of water and a storage facility for which the best use and pumping must be coordinated with releases of water from the surface reservoir. For this, an operating policy consisting of a set of control rules is required indicating volumes of water to be kept in storage or released at given points in time. In such a system, neither of the two sources can meet the demand on its own but the joint use of them could satisfy the demand at an acceptable reliability level. In addition, optimization of the use of the two sources needs to be made so that the cheapest source could be used at its maximum. This is in essence the basic objective of conjunctive use.

Control rules for the management of the two sources are usually based on computer modeling of the supply and demand to predict future water shortages and to assess economic aspects of operating the scheme at the highest possible reliability of supply. Application of techniques such as dynamic programming allows the optimum yield of water for the system to be evaluated for any chosen combination of sources.

In the case of a conjunctive use scheme between a surface water source and a groundwater source, the advantage is that during the dry season groundwater is a more reliable source when available surface runoff is at its minimum. The surface water source can be drawn upon first during the wet season allowing groundwater to recover. The same approach could practically be employed in the conjunctive use of any two sources, be they surface reservoir, aquifer or desalination plant. In the latter case where the desalination costs are very high, this non-conventional source of water could be used only when the other source (surface or groundwater) cannot meet the demand. Thus, only the capital investment of setting up such a plan should be considered since this plant will be switched on and off according to the need for supplementing the demand. The conventional source could be relied upon to its maximum with the expensive sources called upon only to maintain the high reliability normally required for water supply. Such an approach could make desalination an attractive proposition.

Wastewater reuse could also be considered as an extra source of water that could be conjunctively operated with other conventional sources so as to maximize the yield of water from a combination of sources. Treated wastewater from urban centers has a high reliability of supply and during the irrigation season could be used directly for the irrigation of selected crops. During winter, when the demand for it is reduced, this could either be stored in surface reservoirs or used to recharge an aquifer (see section 7.2.6) from which it could be re-pumped during the irrigation season. Conjunctive use of this source of water with other conventional sources could help alleviate water scarcity problems.

The quest for a better use of the available water, which is by far exceeded by the demand under water scarcity conditions, calls for well planned monitoring programs of hydrological information, the application of descriptive and optimizing models and conjunctive use of more than one source.

6.7. The use of groundwater in coping with water scarcity

The physical and storage characteristics of aquifers, large or small, make the use of groundwater essential in alleviating a major part of water scarcity in a region. The major issues pertaining to large aquifers systems are quite different from those of minor ones and could be of great local importance. A good understanding of an aquifer system is required and its operation and management demands greater attention if groundwater is to play a key role in reducing water scarcity.

Managing groundwater reservoirs under the stress conditions of meeting the demand in an environment without sufficient water resources is a very difficult target, particularly when over-exploitation of the aquifers is the norm. Appropriate monitoring of the aquifers and their exploration is essential to support management. Such over-use of groundwater has serious effects on the aquifer and considerable environmental impacts such as the drop of water levels, increase of energy costs for pumping, water quality deterioration, seawater intrusion, land subsidence and collapse, reduction of stream low flows and drying of wetlands. High economic and social impacts also result from these exploitation conditions. Therefore, the main considerations for exploiting and managing an aquifer under scarcity conditions generally aim at combating and overcoming these problems.

Emphasis should be placed on artificial groundwater recharge as a management intervention that could help to partly restore diminished groundwater reserves during periods of surface or other water availability. The same technique could also help to control seawater or other inferior quality water intrusion into the aquifer by establishing favorable controlling hydraulic conditions. Recharge could also be used to improve and further the reuse of treated wastewater. The various techniques available for artificial groundwater recharge, the benefits provided, and the generally positive environmental impacts produced, make artificial recharge an attractive issue for water scarcity regions.

Finally, adopting the conjunctive use of surface- and groundwater, and other non-conventional water sources, provides for sound water resources management seeking to maximize water availability. In this respect, the ability to integrate groundwater storage with surface water storage, or with treated wastewater or water from desalination plants attains significant importance in regions with limited availability of water resources.

A good evaluation of the available water resources and of the demands placed on them, and of the impacts of any exploitation scenario, as well as measures to counteract adverse effects on the aquifers, are very important for the sustainable use of groundwater resources. This is even more important if irreparable damages are to be avoided, and groundwater is to continue to play its important role in coping with meeting the demand in regions under water scarcity.

7. Using non-conventional resources

7.1. Introduction

Whenever good quality water is scarce, water of inferior quality will have to be considered for use in agriculture, irrigation of lawns and gardens, washing of pavements, and other uses not requiring high quality water. Inferior quality water is also designated as non-conventional water or marginal quality water. Non-conventional water can be defined as water that possesses certain characteristics which have the potential to cause problems when it is used for an intended purpose (Pescod, 1992). Thus, the use of non-conventional water requires adoption of more complex management practices and more stringent monitoring procedures than when good quality water is used.

Non-conventional waters most commonly include saline water, brackish water, agricultural drainage water, water containing toxic elements and sediments, as well as treated or untreated wastewater effluents. All these are waters of inferior or marginal quality. Also included under the designation of non-conventional waters are the desalinated water and water obtained by fog capturing, weather modification, and rainwater harvesting.

The expansion of urban populations and the increased population served by domestic water supply and sewerage give rise to greater quantities of municipal wastewater. With the current emphasis on environmental health and water pollution issues, there is an increasing awareness of the need to dispose of these wastewaters safely and beneficially. The use of wastewater in agriculture is already expanding, particularly in water scarcity regions. However, the quantity of wastewater available in most countries will account for only a small fraction of the total irrigation water requirements. Nevertheless, wastewater use will result in the conservation of higher quality water and its use for purposes other than irrigation. The nitrogen and phosphorus content of sewage might reduce the requirements for commercial fertilisers. As the marginal cost of alternative supplies of good quality water will usually be higher in water scarce areas, it is important to incorporate agricultural reuse into water resources and land use planning.

Reuse of treated water for non-agricultural uses is quite small relative to irrigation of agricultural crops. These applications include the reuse of treated industrial effluents for low quality uses in the same industrial plant, the reuse of treated municipal wastewater in aquaculture, for the irrigation of lawns and recreational areas, and for low quality domestic water uses when separated (dual) municipal distribution systems are available.

The increase in food production for the continuously growing world population will have to be met in large proportion by expansion of irrigation. In water scarce regions, irrigation has the ability not only to increase production per unit area of land but also to stabilise production. In arid and semi-arid areas, irrigation is the only reliable means of increasing agricultural production on a sustainable basis. However, good quality water for irrigation is increasingly short since a number of countries are approaching full utilisation of their water resources and priority is being given to uses requiring higher quality water. Therefore water of inferior quality produced from saline aquifers or resulting from drainage waters has to be used/reused for irrigation of agricultural crops along with wastewaters. In case of reuse of drainage waters, agriculture acts both as an utiliser of the water and as a disposal site, so contributing to control of potential environmental impacts from salts carried by those waters.

As for treated effluents, saline water may also be used for non-agricultural purposes such as washing, low quality domestic uses or irrigation of recreational areas. However, the use of saline waters in irrigation has positive impacts for non-agricultural uses because it decreases their demand for good quality water, and the good quality water then becomes available for uses requiring more stringent water quality standards.

Desalinated waters are commonly added to the fresh waters for domestic uses. They are free from toxic substances or pathogens and can, therefore be used to satisfy most human requirements. By contrast, because of its low level of salts and the high costs associated with treatment, desalinised water is less appropriate for agricultural uses.

Fog capturing is used in isolated arid areas in mountains and islands where the occurrence of fog is common but rainfall is rare. Water production by this process is small but may be essential for assuring living conditions for small populations in these areas. An alternative for isolated households and villages in remote areas where surface- or groundwater is not easily available for domestic uses or animal drinking is the use of roof-water which can be captured and stored in cisterns. Water harvesting systems provide for irrigation of vegetables, fruit trees and subsistence crops. Water harvesting has been analysed in Section 5.4.

Cloud seeding is a process of augmenting rainfall by adding substances to the cold clouds that act as nuclei for the formation of large water drops that otherwise would not fall to the ground. Its interest is however limited by the lack of cold wet air masses travelling over the arid low-lying areas where populations live. Water importation mainly consists of transferring water from a basin where it may be in excess to the demand into another basin where water demand is much above the natural supply. Generally this concerns long distance water transfer from basins in sub-humid to humid regions into semi-arid areas. These transfers may be quite effective from a water management perspective but they may create large environmental and developmental impacts in both the region from where the water is transferred and the region where it becomes available unless appropriate management and monitoring is applied.

7.2. Wastewater use

7.2.1. Wastewater and effluent characteristics

7.2.1.1. General wastewater characteristics

Municipal wastewater is mainly comprised of water with relatively small concentrations of suspended and dissolved organic and inorganic solids. Organic substances include carbohydrates, lignin, fats, soaps, synthetic detergents, proteins and their decomposition products, as well as various natural and synthetic organic chemicals from the process industries. In arid and semi-arid countries, water use is often fairly low and sewage tends to be very strong, as indicated in Table 7.1 for Amman, Jordan, where per capita water use is only 90 l/day while 200 l/day is common in water abundant areas.

TABLE 7.1. Major constituents of typical domestic wastewater (Pescod, 1992).

Constituent	Concentration, mg/l			
	Strong	Medium	Weak	Amman
Total dissolved solids (TDS)	850	500	250	1170
Suspended solids	350	200	100	900
Nitrogen (as N)	85	40	20	150
Phosphorous (as P)	20	10	6	25
Alkalinity (as $CaCO_3$)	200	100	50	850
BOD_5 [(a)]	300	200	100	770

[(a)] Biochemical oxygen demand at 20oC over 5 days, which is a measure of the biodegradable organic matter in the water.

7.2.1.2. Pathogens in wastewaters

Municipal wastewater also contains a variety of inorganic substances from domestic and industrial sources, including a number of potentially toxic elements, including heavy metals, such as arsenic, cadmium, chromium, copper, lead, mercury and zinc. This water might also be at phytotoxic levels, which would limit its use in agriculture. From the point of view of health, the contaminants of greatest concern are the pathogenic micro- and macro-organisms. Pathogenic viruses, bacteria, protozoa and helminths may be present in raw municipal wastewater and will survive in the environment for long periods. Pathogenic bacteria are generally present in wastewater at much lower levels than the coliform group of bacteria, which are easy to identify and enumerate as total coliforms/100 ml. The *Escherichia coli* are the most widely adopted indicator of faecal pollution and they can also be isolated and identified fairly simply, with their numbers usually being given in the form of faecal coliforms (FC)/100 ml of wastewater.

The principal health hazards associated with the chemical constituents of wastewaters arise from the contamination of crops or groundwater. Particular concern is attached to the cumulative poisons, which comprise mainly the heavy metals, and carcinogens, which are mainly organic chemicals. The World Health Organization guidelines for drinking water quality (WHO, 1984) include limit values for the organic and toxic substances based on acceptable daily intakes. These can be adopted directly from groundwater protection

purposes. However, considering the possible accumulation of certain toxic elements in plants (for example, cadmium and selenium), the intake of toxic materials through eating the crops irrigated with contaminated wastewater must be carefully assessed.

Pathogenic organisms give rise to the greatest health concern in the use of wastewaters. In areas of the World where helminthic diseases caused by *Ascaris* and *Trichuris* spp. are endemic in the population and where raw untreated sewage is used to irrigate salad crops and/or vegetables eaten uncooked, transmission of these infections is likely to occur through the consumption of such crops. Further evidence was provided to show that cholera can be transmitted through the same channel. There is also evidence that cattle grazing on fields freshly irrigated with raw wastewater, or drinking from raw wastewater canals or ponds, can become heavily infected with the cysticerosis disease. Indian studies have shown that sewage farm workers exposed to raw wastewater in areas where *Ancylostoma* (hookworm) and *Ascaris* (nematode) infections are endemic have significantly higher levels of infection than other agricultural workers. More detailed information on health risks and vector-borne diseases are given by Birley (1989), Mara and Cairncross (1989) and Tiffen (1989).

In respect of the health impact of use of wastewater in irrigation, pathogenic agents are ranked as shown in Table 7.2. However, negative health effects were only detected in association with the use of raw or poorly treated wastewater, while inconclusive evidence suggested that appropriate wastewater treatment could provide a high level of health protection (Pescod, 1992). Risks from diseases such as schistosomiasis, clonorchiasis, and taeniasis vary from high to nil depending on local circumstances (WHO, 1989).

TABLE 7.2. Relative health impact of pathogenic agents (Pescod, 1992).

Risk	Agents
High risk (high incidence of excess infection)	Helminths (*Ancylostoma*, *Ascaris*, *Trichuris* and *Taenia*)
Medium Risk (low incidence of excess infection)	Enteric bacteria (*Vibrio cholera*, *Salmonella typhosa*, *Shigella*)
Low Risk (low incidence of excess infection)	Enteric viruses (Viral diarrhoeas, hepathitis A)

The following microbiological parameters are particularly important from the health point of view (Pescod, 1992; Mara and Cairncross, 1989):

- Coliforms and faecal coliforms, whose survival time is up to 60 days in water and 70 days in the soil. The coliform group of bacteria comprises mainly species of the genera *Citrobacter*, *Enterobacter*, *Klebsiella,* and *Escherichia coli*, the latter being the predominant species among faecal coliforms. The E. coli count is a main indicator for wastewater use in agriculture.
- Faecal *Streptococci*. This group includes species mainly associated with animals such as *Streptococcus bovis* and *S. equinus*, as well as other species with a wider distribution (e.g. *S. faecalis* and *S. faecium*), which occur both in man and in other animals.

- *Clostridium perfringens*. This bacterium is an exclusively faecal spore-forming anaerobe, normally used to detect intermittent or previous pollution of water. It may be useful in wastewater quality reuse studies because *C. perfringens* may have survival characteristics similar to those of viruses or even helminth eggs.
- *Salmonella spp*, having a survival time similar to the faecal coliforms. Several species may be present in raw sewage from urban communities in tropical developing countries, including *S. typhi* that is the causative agent for typhoid. It is has been estimated that a count of 7000 *Salmonellae* /litre is typical in a tropical urban sewage with similar numbers of *Shigellae* and near 1000 *Vibrio cholera*. These have a shorter survival time, so when the removal of *Salmonellae* is achieved these other pathogenic bacteria are probably also removed.
- *Enteroviruses*, whose survival time may attain 120 days in water. These may give rise to diseases such as Poliomyelitis and Meningitis, or to a range of minor illness such as respiratory infections. Although there is no strong epidemiological evidence for the spread of these diseases via sewage irrigation systems, there is some risk and it is desirable to know to what extent viruses are removed by treatment, especially under tropical conditions.
- *Rotaviruses*, which are known to cause gastro-intestinal problems and to be more persistent than enteroviruses. It has been considered that the removal of viruses in wastewater treatment occurs in parallel with the removal of suspended solids, as most virus particles are solids-associated. Hence, the measurement of suspended solids in treated effluents should be routinely carried out.
- Intestinal Nematodes, having a survival time of several months. Related infections, in particular from *Ascaris lumbricoides*, can be spread by effluent reuse practices. The eggs of *A. lumbricoides* are fairly large (45-70 μm x 35-50 μm) and several techniques for enumeration of nematodes have been developed.

7.2.2. Wastewaters characteristics relative to agricultural use

The quality of irrigation water is of particular importance in arid zones where high rates of evaporation occur, with consequent salt accumulation in the soil profile. The physical and mechanical properties of the soil, such as dispersion of particles, stability of aggregates, and permeability, are very sensitive to the type of exchangeable ions present in irrigation water. Thus, when effluent use is being planned, several factors related to soil properties must be considered. Ayers and Westcot (1985) provide appropriate recommendations on these water quality aspects. Questions relative to the use of saline waters in agriculture are dealt with in Section 7.3.

Another aspect of agricultural concern is the effect of dissolved solids (TDS) in irrigation water on the growth of plants. Dissolved salts increase the osmotic potential of soil water and therefore increase the amount of energy which plants must expend to extract water from the soil. As a result, growth and yield of most plants decline progressively as osmotic pressure increases due to the presence of salts in the soil and the soil water (see Section 7.3.).

Many of the ions carried in the wastewaters are harmless or beneficial at relatively low concentrations, but may become phytotoxic at high concentrations, or may negatively

affect several metabolic processes.

Important agricultural water quality parameters include a number of specific properties of water that are relevant in relation to the yield and quality of crops, maintenance of soil productivity and protection of the environment. These are analysed in the next section. These parameters mainly consist of certain physical and chemical characteristics of the water, such as (Pescod, 1992; Kandiah, 1990; Rhoades *et al.*, 1992):

- Total salt concentration or the total dissolved solids, because the salinity of the soil is directly affected by the salinity of the irrigation water.
- Electrical conductivity, which is used to indicate the total ionised constituents of water and is closely correlated with the total salt concentration.
- Sodium adsorption ratio (SAR), because when sodium is present in the soil in exchangeable form, it causes adverse physico-chemical changes, particularly to soil structure. Due to the ability of sodium to disperse the soil aggregates, a crust is formed on the soil surface reducing the infiltration rates and affecting germination and seedling emergence. The SAR is defined by the ionic ratio.

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \tag{7.1}$$

  where the ionic concentrations of sodium (Na), calcium (Ca) and magnesium (Mg) are expressed in me/l. If significant precipitation or dissolution of calcium due to the effect of carbon dioxide (CO_2), bicarbonate (HCO_3^-) and total salinity of the water (EC_w) is suspected, the adjusted sodium adsorption ratio (SAR_{adj}) can be used as reported by Ayers and Westcot (1985).
- Toxic ions. When at concentrations above threshold values, they can cause plant toxicity problems, which affect growth and yield of crops. The degree of damage depends on the crop, its stage of growth, and the concentration of the ions. The most common phytotoxic ions in municipal sewage and treated effluents are boron (B), chloride (C1), and sodium (Na).
- Trace elements. Attention should be paid to trace elements in sewage effluents if industrial wastewater is included. The main ones are Aluminium (Al), Beryllium (Be), Cobalt (Co), Fluoride (F), Iron (Fe), Lithium (Li), Manganese (Mn), Molybdenum (Mo), Selenium (Se), Tin (Sn), Titanium (Ti), Tungsten (W) and Vanadium (V).
- Heavy metals, a special group of trace elements, which have been shown to cause health hazards when taken up by plants: Arsenic (As), Cadmium (Cd), Chromium (Cr), Copper (Cu), Lead (Pb), Mercury (Hg) and Zinc (Zn).
- pH. The normal pH range for irrigation water is from 6.5 to 8.4. pH values outside this range indicate water is abnormal in quality.

7.2.3. Wastewater treatment

Wastewater treatment aims at safe disposal of human and industrial effluents, without danger to human health or damage to the natural environment. Irrigation with wastewater is

both disposal and utilisation. Some degree of treatment needs to be provided to raw municipal wastewater before it can be used for agricultural and landscape irrigation, aquaculture or other uses. The required quality of effluent will depend on the proposed water uses, crops to be irrigated, soil conditions and the irrigation system. In aquaculture, more reliance will have to be placed on control through wastewater treatment.

The most appropriate wastewater treatment for agricultural uses is that which will produce an effluent meeting the recommended microbiological and chemical quality guidelines both at low cost and with minimal operational and maintenance requirements (Arar, 1988). Adopting as low a level of treatment as possible while achieving the desired results is important, especially in developing countries. In practice, it may be better to design the reuse system to accept a low-grade of effluent rather than to rely on advanced treatment processes to produce a reclaimed effluent which continuously meets a stringent quality standard.

The design of wastewater treatment plants is usually based on the need to reduce organic and suspended solids loads to limit pollution of the environment. Pathogen removal has very rarely been considered an objective but, for reuse of effluents in agriculture, this must be of primary concern (Hillman, 1988). Treatment to remove wastewater constituents that may be toxic or harmful to crops, aquatic plants and fish is normally not economically feasible. However, the removal of toxic elements and pathogens that may affect human health needs to be considered.

The daily variations in flow from a municipal treatment plant make it generally not feasible to irrigate with effluent directly from the treatment plant. Some form of short-term storage of treated effluent is necessary to provide a relatively constant supply of reclaimed water for efficient irrigation, although additional benefits result from storage in reservoirs.

7.2.3.1. Conventional wastewater treatment

Conventional wastewater treatment consists of a combination of physical, chemical, and biological processes and operations to remove solids, organic matter and, sometimes, nutrients from wastewater. Different degrees of treatment are considered (Pescod, 1992):

(a) *Preliminary treatment*, where the objective is the removal of coarse solids and other large materials from the raw wastewater. Treatment operations include coarse screening, grit removal in most small treatment plants and, in some cases, comminution (trituration) to reduce the size of large particles so as to remove them in the form of sludge in subsequent treatment processes.

(b) *Primary treatment*. Its objective is the removal of settable organic and inorganic solids by sedimentation, and the removal of materials that float by skimming. Large fractions of the biochemical oxygen demand (BOD_5), total suspended solids, oil and grease are then removed. Some organic nitrogen, organic phosphorous and heavy metals associated with those solids are also removed, but not colloidal and dissolved constituents. It may be considered sufficient treatment if the wastewater is to be used to irrigate crops that are not consumed by humans or to irrigate orchards, vineyards, and some processed food crops. However, to prevent potential nuisance conditions in reservoirs, which may affect nearby populations and workers, some form of secondary treatment may be required even in the case of non-food crop irrigation.

Primary sedimentation tanks or clarifiers are used. The sludge of settled solids is removed from the bottom of tanks and floating solids are swept across the tank surface by water jets or mechanical means. In large sewage treatment plants, primary sludge is commonly processed biologically by anaerobic digestion. Gas containing methane is then produced and can be used as an energy source. In small sewage treatment plants, sludge is processed by aerobic digestion, storage in sludge lagoons, land application, and others.

(c) *Secondary treatment*, where the objective is the further treatment of the primary effluent to remove the residual organics and suspended solids. In most cases, secondary treatment involves the removal of biodegradable dissolved and colloidal organic matter using aerobic biological treatment processes. Several aerobic biological processes are used for secondary treatment, differing primarily in the manner in which oxygen is supplied to the microorganisms and in the rate at which microorganisms metabolise the organic matter.

High-rate biological processes are characterised by relatively small reactor volumes and high concentrations of microorganisms compared with low rate processes. The microorganisms must be separated from the treated wastewater by sedimentation to produce clarified secondary effluent. The biological solids removed during secondary sedimentation are normally combined with primary sludge for sludge processing. Common high-rate processes include the activated sludge processes, trickling filters or biofilters, oxidation ditches, and rotating biological contactors (RBC). A combination of two of these processes in series (e.g., biofilter followed by activated sludge) can be used to treat municipal wastewater containing a high concentration of organic material from industrial sources.

High-rate biological treatment processes remove nearly 85% of the BOD_5 and suspended solids as well as some of the heavy metals. Activated sludge generally produces an effluent of slightly higher quality than biofilters or RBCs. When coupled with a disinfection step such as chlorination, these processes can provide substantial but not complete removal of bacteria and viruses. However, they remove very little of the phosphorous, nitrogen, non-biodegradable organics, or dissolved minerals.

(d) *Tertiary and/or advanced treatment*, which is employed when specific undesirable wastewater constituents cannot be removed by secondary treatment. This may be the case for nitrogen, phosphorous, additional suspended solids, refractory organics, heavy metals and dissolved solids.

Where the risk of public exposure to the treated water is high, the intent of the advanced treatment is to minimise the probability of human exposure to enteric viruses and other pathogens. Because effective disinfection is believed to be inhibited by suspended and colloidal solids in the water, these solids must be removed by advanced treatment before the disinfection step. Therefore, the sequence of treatment often is secondary treatment followed by chemical coagulation, sedimentation, filtration, and disinfection. This level of treatment is assumed to produce an effluent free from detectable viruses.

(e) *Disinfection*. Disinfection normally involves the injection of a chlorine solution (5 to 15 mg/l) at the head end of a chlorine contact basin. Ozone and ultra violet irradiation can also be used to meet advanced wastewater treatment requirements. A chlorine contact time as long as 120 minutes is sometimes required. In Near East countries

adopting tertiary treatment, the tendency has been to introduce pre-chlorination before rapid-gravity sand filtration and post-chlorination afterwards. A final ozonation treatment after this sequence has seldom been considered (Al-Nakshabandi *et al*., 1997).

7.2.3.2. Natural biological treatment systems

Natural low-rate biological treatment systems for the treatment of municipal sewage tend to be less costly and sophisticated in operation and maintenance than the high-rate biological processes mentioned above. They may be more effective in removing pathogens if properly designed and not overloaded. Natural biological treatment systems consist of (Pescod, 1992):

(a) *Stabilisation ponds*. Stabilisation ponds are the preferred wastewater treatment process for effluent use in agriculture in developing countries. These systems are designed to achieve different forms of treatment in a series of three stages. The number of stages used will depend on the organic strength of the input waste and the effluent quality objectives. Strong wastewaters, having BOD_5 > 300 mg/l, are introduced into first-stage anaerobic ponds, which achieve a high rate of removal. Where anaerobic ponds are environmentally unacceptable (mainly because of odour and flies) or are not required (e.g. for weaker wastes i.e. with low BOD_5), wastewater is discharged directly into primary facultative ponds. Effluent from first-stage anaerobic ponds will overflow into secondary facultative ponds which comprise the second-stage of biological treatment. Maturation ponds to provide tertiary treatment are introduced following the primary or secondary facultative ponds, if further pathogen reduction is necessary.

Solids in the influent to a facultative pond and excess biomass produced in the pond will settle out forming a sludge layer at the bottom. The benthic layer will be anaerobic and, as a result of anaerobic breakdown of organics, will release soluble organic products to the water column above. Organic matter dissolved or suspended in that water is metabolised by heterotrophic bacteria, with uptake of oxygen, as in conventional aerobic biological treatment processes. Unlike in conventional processes, the dissolved oxygen utilised by the bacteria in facultative ponds is replaced through photosynthetic oxygen produced by microalgae rather than by aeration equipment. High temperature and sunlight create conditions which encourage algae to utilise the carbon dioxide (CO2) released by bacteria in breaking down the organic components of the wastewater and to take up nutrients, mainly nitrogen and phosphorous. This contributes to the overall removal of BOD_5 in facultative ponds. However, the organic loading must be strictly limited otherwise not enough oxygen will be produced. Wind is important to the satisfactory operation of facultative ponds for mixing the contents and to prevent thermal stratification that would cause anaerobiosis and subsequent failure of the processes.

The effluent from facultative ponds normally contains at least 50 mg/l BOD_5. If lower BOD_5 concentration is required it will be necessary to use maturation ponds. A more important function of maturation ponds, however, is the removal of excreted pathogens. Longer retention in anaerobic and facultative pond systems will make them more efficient than conventional treatment processes in removing pathogens. Effluents from a facultative pond treating municipal sewage generally require further

treatment. Maturation ponds should then be designed to achieve a given reduction of faecal coliforms (FC). Protozoan cysts and helminth eggs are removed by sedimentation in stabilisation ponds. A series of ponds with overall retention of 20 days or more will produce an effluent totally free of cysts and ova (Feachem *et al.*, 1983, cited by Pescod, 1992). Pathogen die-off, is linked to algal activity. The coliform and faecal coliform die-off coefficients vary with retention time, water temperature, organic loading, total BOD_5 concentration, pH and pond depth (Saqqar, 1988, cited by Pescod, 1992).

(b) *Overland treatment of wastewater*. In overland flow treatment, the effluent is distributed over gently sloping grassland on fairly impermeable soils. Ideally, the wastewater moves evenly down the slope to collecting ditches at the bottom edge of the area. Suspended and colloidal organic materials are then removed by sedimentation and filtration through the surface grass and organic layers. Overland flow systems also remove pathogens from sewage effluent at levels comparable with conventional secondary treatment systems, without chlorination. This form of land treatment requires intermittent applications of effluent (usually treated) alternating with resting of the land, to allow the soil to react with the sediments and for grass cutting. Basic site characteristics and design features for overland flow treatment have been suggested (EPA, 1977, cited by Pescod, 1992). The impact on groundwater should be considered in the case of highly permeable soils. The application rate for wastewaters will depend principally on the type of soil, the quality of wastewater effluent and the physical and biochemical activity in the near-surface environment (Middlebrooks *et al.*, 1982, cited by Pescod, 1992).

The cover crop is an important component of the overland flow system since it should prevent soil erosion, provide nutrient uptake and serve as a fixed-film medium for biological treatment. Crops best suited to overland flow treatment are grasses with a long growing season, high moisture tolerance and extensive rooting. Reed canary grass, rye grass and tall fescue are among the suitable species.

(c) *Macrophyte treatment*. This occurs in maturation ponds that incorporate floating, submerged or emergent aquatic species (macrophytes). They can be used for upgrading effluents form stabilisation ponds, thus acting as maturation ponds. Macrophytes take up large amounts of inorganic nutrients (N and P) and heavy metals (Cd, Cu, Hg and Zn).

Among the floating macrophytes, having large root systems and very efficient nutrient extraction, are the water hyacinth, *Eichornia crassipes,* able to double in mass about every 6 days, and the coontail, *Ceratophyllum demersum*. The aquatic vascular plants also serve as living substrates for microorganisms that remove BOD and nitrogen, and achieve reductions in phosphorus, heavy metals and some organics through plant uptake. The basic function of the macrophytes in the latter mechanism is to assimilate, concentrate and store contaminants on a short-term basis. Subsequent harvest of the plant biomass results in permanent removal of stored contaminants from the pond treatment system. Fly and mosquito breeding are a problem in floating macrophyte ponds. This nuisance can be partially controlled by introducing into the ponds fish species such as *Gambusia* and *Peocelia* that eat these larvae. Pathogen die-off is poor in macrophyte ponds as a result of light shading and the lower dissolved oxygen and pH.

Natural and artificial wetlands and marshes having emergent macrophytes can also be used to treat raw sewage and partially-treated effluents. The main species of emergent macrophytes (reeds) are *Phragmites communis* and *Scirpus lacstris.* These macrophytes not only take up the inorganic nutrients but also create a favourable environment in the root zone for microorganisms, through pathways created by their highly developed root systems. BOD and nitrogen are then removed by bacterial activity. Aerobic treatment takes place in the rhizosphere, since oxygen passes to it from the atmosphere through leaves, stems, and roots, while an anoxic and anaerobic treatment takes place in the surrounding soil. Suspended solids in the sewage are aerobically composted in the above ground layer of decaying vegetation formed from dead leaves and stems. Nutrients and heavy metals are then removed by plant uptake.
The growth rate and pollutant assimilative capacity of emergent macrophytes such as *Phragmites communis* and *Scirpus lacstris* are limited by the culture system, wastewater loading rate, plant density, climate and management factors.

(d) *Nutrient film technique*. The nutrient film technique (NFT) is a modification of the hydroponics plant growth system, in which plants are grown directly on an impermeable surface to which a thin film of wastewater is continuously applied. Root production above the impermeable surface is high and the large root surface area traps and accumulates matter. Plant growth produces nutrient uptake, and provides shading for protection against the development of algae, while the large mass of roots and accumulated material serve as living filters.

7.2.4. Minimising health hazards in wastewater use in irrigation

A potential for disease transmission exists when wastewater is used for irrigation, because pathogens brought with the wastewater can survive for many days in the soil or on the crop. Factors influencing transmission of disease include the degree of wastewater treatment, the crops grown, the irrigation method used to apply the wastewater, and the cultural and harvesting practices used.

In general, three levels of *public health risk* are considered (Westcot, 1997):

(a) Lowest risk to the consumer, but field worker protection is needed.
   1. Crops not for human consumption (e.g. fiber crops such as cotton and sisal).
   2. Crops normally processed by heat or drying before human consumption (e.g. grains, oilseeds, sugar beet).
   3. Vegetables and fruits grown exclusively for canning or other processing that effectively destroys pathogens.
   4. Fodder crops and other animal feed crops that are sun-dried and harvested before consumption by animals (hay, silage).

(b) Increased risk to consumer, field worker and handler.
   1. Pasture, green fodder crops.
   2. Crops for human consumption that do not come into direct contact with wastewater, on condition that fruits are not picked off the ground and that sprinkler or spray irrigation is not used (e.g. tree crops, vineyards).

3. Crops for human consumption normally eaten only after cooking (e.g. potatoes, eggplant, beetroot).
4. Crops for human consumption, the peel of which is not eaten (e.g. melons, citrus fruits, bananas, nuts, groundnuts).
5. Any crop not identified as high-risk when sprinkler irrigation is used.

(c) Highest risk to consumer, field worker and handler.

1. Any crops eaten uncooked and grown in close contact with wastewater effluent (fresh vegetables such as lettuce or carrots, or spray-irrigated fruits).
2. Landscape irrigation with public access (parks, lawns, golf courses).

The possible infection of field workers results from direct contact with the crop or soil in the area where wastewater is used. This path is directly related to the level of protection needed for field workers. The only feasible means of dealing with the worker safety problem is to adopt preventive measures against infection. The following *risk situations for field workers* are often identified (Westcot, 1997):

(a) Low risk of infection.

- Mechanised cropping practices.
- Mechanised harvesting practices.
- Irrigation ceasing long before harvesting.
- Long dry periods between irrigations.

(b) High risk of infection.

- High wind and dust areas.
- Hand cultivation and hand harvesting.
- Moving of sprinkler or other irrigation equipment.
- Direct contact with irrigation water.

To minimise health hazards for field workers preventive measures are required. These include wearing protective clothing, including impermeable boots that prevent any direct skin contact with the wastewater, the maintenance of high levels of hygiene, and immunisation against infections likely to occur.

International guidelines or standards for the microbiological quality of irrigation water used on a particular crop do not exist. Because there is a lack of direct epidemiological data, the standards and guidelines for the quality of wastewater used for irrigation are focused on effluent standards at the wastewater treatment plant, rather than at the point of use. These standards are most often used for process control at wastewater treatment plants. Based on an epidemiological review, WHO adopted the water quality guidelines for wastewater use in agriculture shown in Table 7.3.

These guidelines recommend less stringent values for faecal coliforms than were previously recommended, but are stricter than previous standards concerning the need to reduce helminth egg concentrations in effluent. The purpose of applying the helminth standard throughout all cropping systems was to increase the level of protection for agricultural workers, who are at high risk from intestinal nematode infection (Mara and Cairncross, 1989). Meanwhile, it was implied that if the recommended helminth egg limit could be reached, that equally high removals of all protozoa would be achieved. It was also

concluded that no bacterial guideline was needed for protection of the agricultural worker since there was little evidence indicating a risk to such workers from bacteria, and some degree of reduction in bacterial concentration would be achieved with efforts to meet the helminth levels.

The guidelines in Table 7.3 are for the microbiological quality of treated effluent from a wastewater plant when that water is intended for irrigation. They should be used as design goals in planning wastewater treatment plants, but they are not intended as standards for quality monitoring of irrigation water (Mara and Cairncross, 1989). However, because urban populations grow enormously, the degree of river and irrigation water supply contamination in developing countries will likely increase. Pressure will also increase to use partially treated wastewater for irrigation until adequate treatment facilities can be constructed. Thus, there is an immediate need to control wastewater use in high risk cropping systems such as vegetable crop production. Since guidelines or regulations that define the quality of water that can be safely applied to irrigation do not exist, the guidelines of WHO could be used as irrigation water standards for regulating cropping practices. These guidelines could be applied in areas where wastewater is utilised directly for irrigation or where use is indirect by diversion of contaminated river water supplies.

TABLE 7.3. Recommended microbiological quality standards for wastewater use in irrigation[1] (WHO, 1989).

Category	Reuse condition	Exposed group	Intestinal nematodes[2] (arithmetic mean no. of eggs/litre)[3]	Faecal coliforms (geometric mean no. per 100 ml)[3]	Wastewater treatment expected to achieve the required microbiological quality
A	Irrigation of crops likely to be eaten uncooked, sports fields and public parks[4]	Workers, consumers, public	≤ 1	≤ 1000[4]	A series of stabilisation ponds designed to achieve the microbiological standard indicated or equivalent treatment
B	Irrigation of cereal crops, crops for industrial processing, fodder crops, pastures and tree crops[5]	Workers	≤ 1	No standard recommended	Retention in stabilisation ponds for 8-10 days or equivalent helminth and faecal coliform removal
C	Localised irrigation (drip or subsurface irrigation) of crops in category B if exposure of workers and public does not occur	None	Not applicable	Not applicable	Pre-treatment as required by the irrigation technology but not less than primary sedimentation

[1] Guidelines may be modified following local epidemiological, socio-cultural and environmental studies.
[2] *Ascaris* and *Trichuris* spp. and hookworms.
[3] During the irrigation period.
[4] To be reduced to 200 FC/100 ml for public lawns where the public may be in direct contact.
[5] For fruit trees, irrigation should stop two weeks before fruits are harvested and no fruits should be picked from the ground. Sprinkler or spray irrigation should not be used.

Indicative expected removal levels of pathogens are shown in Table 7.4 for various treatment processes. Results depend not only upon the treatment as indicated in Table 7.5, but also on time of detention (Mara and Cairncross, 1989; Westcot, 1997).

As stated by FAO (Westcot, 1997), until sufficient epidemiological information is available, it seems prudent to utilise the WHO (1989) guidelines for controlling the quality of water used in irrigation. These guidelines should be a performance goal to achieve for those water supplies which presently exceed this level, and for cropping areas that would present a high risk of infection. Using the guidelines as irrigation standards would help to:

- Assess the extent of contamination.
- Reduce the disease infection risk until suitable wastewater treatment is adopted.
- Improve the basic health level in rural areas; and
- Provide data that can be used in planning for wastewater management.

Difficulties for application of the WHO guidelines in monitoring result from the lack experience in monitoring helminth egg concentrations in irrigation water and insufficiency of techniques available. Therefore, monitoring should focus on the faecal coliform guidelines, for which techniques are available and have been widely used in USA.

TABLE.7.4. Qualitative comparison of various treatment systems (adapted from Westcot, 1997).

Criteria	Factor considered	Package plant	Activated sludge plant	Extended aeration activated sludge	Biological filter	Oxidation ditch	Aerated lagoon	Waste stabilisation pond system
Plant performance	BOD removal	F	F	F	F	G	G	G
	FC removal	P	P	F	P	F	G	G
	SS removal	F	G	G	G	G	F	F
	Helminth removal	P	F	P	P	F	F	G
	Virus removal	P	F	P	P	F	G	G
Economic factors	Simple and cheap	L	L	L	L	M	M	H
	Simple operation	L	L	L	M	M	L	H
	Land requirement	H	H	H	H	H	M	L
	Maintenance cost	L	L	L	M	L	L	H
	Energy demand	L	L	L	M	L	L	H
	Sludge removal cost	L	M	M	M	L	M	H

BOD – biochemical oxygen demand; FC – faecal coliform; SS – total suspended solids.
G –good; F – fair; P – poor. H – high; M – medium; L – low (e.g. low demanding or low cost).

To minimise the health risk from using wastewater in irrigation, the prime approach is to treat the wastewater to the level recommended above. However the reality is that untreated or insufficiently treated wastewaters are still used for irrigation. Then, the

application of crop restrictions can be the most effective measure to protect the consumer. In fact, crop restrictions constitute the most widely used measure to protect public health. Crop restrictions focus on salad or vegetable crops that are normally eaten raw as indicated before.

TABLE 7.5. Expected removal of enteric pathogenic microorganisms in various treatment systems (Mara and Cairncross, 1989).

Treatment process	Removal (log_{10} units) *			
	bacteria	helminths	virus	cysts
Primary sedimentation, plain	0-1	0-2	0-1	0-1
Primary sedimentation chemically assisted	1-2	1-3(A)	0-1	0-1
Activated sludge(1)	0-2	0-2	0-1	0-1
Biofiltration(2)	0-2	0-2	0-1	0-1
Aerated lagoon(2)	1-2	1-3(A)	1-2	0-1
Oxidation ditch(1)	1-2	0-2	1-2	0-1
Disinfection(3)	2-6(A)	0-1	0-4	0-3
Waste stabilisation ponds(4)	1-6(A)	1-3(A)	1-4	1-4
Effluent storage reservoirs(5)	1-6(A)	1-3(A)	1-4	1-4

*4 log_{10} units is equivalent to 10^{-4} or 99.9 % removal.
(1) including secondary sedimentation.
(2) including settling pond.
(3) chlorination or ozonation.
(4) performance depends on the number of ponds in series and other environmental factors.
(5) performance depends on retention time.
(A) with good design and proper operation the recommended guidelines are achievable.

Crop restrictions need a strong institutional framework and the capacity to monitor and control compliance with the regulations. The following factors favour the adoption of crop restrictions (Mara and Cairncross, 1989):

- a law-abiding society or strong law enforcement,
- allocation of wastewater is controlled by a public body that has legal authority to enforce crop restrictions,
- the irrigation water conveyance and distribution system is controlled by strong central management,
- there is high demand and price advantage for the unrestricted crops,
- there is little market pressure in favour of the excluded crops, and
- wastewater is used by a small number of large farms.

On the contrary, very large, dispersed irrigation schemes and those having poor or weak management make it difficult to enforce crop restrictions. Difficulties also occur when producers are mainly small farmers and the market prices do not favour the adoption of lower risk crops. In many developing countries, wastewater, including untreated effluent, is discharged directly to surface waters and these are diverted downstream for irrigation purposes. This leads to widespread distribution of the wastewater and makes crop restriction extremely difficult.

Irrigation practices should be designed according to the quality of wastewater being used. Questions concerning salinity hazards associated with wastewater are described in Section 7.3. Several aspects referring to the control of health hazards have been dealt with above. However, the selection of methods of irrigation with wastewater to comply with guidelines for controlling health risks deserves particular attention.

Irrigation methods are briefly described in Section 8.8. Readers may get more appropriate details on the irrigation methods and their respective characteristics and performance in specialised literature (e.g. Tiercelin, 1998; Pereira and Trout, 1999). The irrigation methods differ on several aspects as summarised in Table 7.6. They mainly concern:

- the probability of direct contact of workers with the irrigation water; which refers to the need for adopting more stringent preventive measures,
- the direct contact of the water with the harvestable yield that implies the need for more care on consumer protection measures,
- the foliar contact with the water that may cause phytotoxic problems to the crop,
- the capability for avoiding salt concentration in the crop root zone, which would cause soil degradation.

Aspects relative to health risk reduction have been discussed above and may be found in several references such as Mara and Cairncross (1989), Pescod (1992), Westcot (1997). Several case studies are given by Biswas and Arar (1988), Pescod and Arar (1988), and Mara and Cairncross (1989).

Toxicity hazards to the crops are well covered by Ayers and Westcot (1985). Their suggested controls mainly rely on avoiding direct contact between the water charged with toxic ions and the crop leaves and/or other sensitive parts of the crop. Dilution of ion concentrations by mixing charged waters with fresh water may be considered but is generally more costly than to select an irrigation method where such foliar contact is minimised.

The salt accumulation in the root zone is generally controlled by leaching of the salts from the root zone naturally when rainfall is abundant, or by applying a leaching fraction with the irrigation water. Leaching with the irrigation water is carefully dealt with by Rhoades *et al.* (1992), and is briefly discussed in Section 7.3.4. The appropriate application of a leaching fraction depends on the irrigation method and the performance of the irrigation system. Practising over-irrigation to be sure that salts are leached down from the root zone is common but this produces excessive percolation to the groundwater. The groundwater then rises close to the soil surface, and the groundwater quality can be degraded. Therefore, to avoid problems due to deep percolation, drainage has to be considered. However, problems may be controlled easily if the irrigation system is designed carefully allowing for control of volumes applied and for an even distribution of water over the field.

Summarising, the safe use of wastewater in irrigation requires not only compliance with guidelines for the control of health risks, but also well designed and efficient irrigation systems. Case study examples are provided in the literature (e.g. Oron *et al*., 1999, Loudon, 2001; Ragab *et al.*, 2001).

TABLE 7.6. Evaluation of the irrigation methods for irrigation with wastewater.

Irrigation methods	Human contact (health hazard)	Contact with fruits and harvestable yield (contamination hazard)	Salt accumulation in the root zone (salinity hazard)	Foliar contact (toxicity hazard)
Basin irrigation and border irrigation	Likely to occur, mainly when water is controlled manually. Preventive measures including clothing requirements	Not occurring for tree crops and vines, and most horticultural and field crops. May occur for low vegetable crops such as lettuce and melon	Not likely to occur except for the under-irrigated parts of the field when uniformity of water application is very poor	Possible for bottom leaves in low crops (e.g. lettuce, melon) and fodder crops. Possible during first stage of growth of annual crops
Corrugated basin irrigation	Likely to occur when water is controlled manually, less when automation is adopted. Preventive measures including clothing are required	Not likely to occur because crops are grown on ridges	Salts tend to accumulate on the top of the ridge. Leaching prior to seeding or planting is required for assuring germination and plant establishment	Exceptionally because crops are grown on ridges and water flows in furrows between them
Furrow irrigation	Likely to occur, when water is controlled manually, less when automation is adopted	Not likely to occur because crops are grown on ridges	Salts tend to accumulate on the top of the ridge. Leaching is required prior to seeding/planting	Exceptionally because crops are grown on ridges
Sprinkler irrigation	Generally workers are not in the field when irrigating but they may have contact with wetted equipment. Small drops into the air should be avoided	Fruits and harvestable yield are contaminated	Not likely to occur except for the under-irrigated parts of the field resulting from low uniformity of water application	Severe leaf damage can occur affecting yields
Micro irrigation: Drip and subsurface irrigation	Not likely to occur except contact with wetted irrigation equipment	Not likely to occur	Not likely to occur except for the under-irrigated parts of the field resulting from low uniformity of water application	Not likely to occur
Micro irrigation: Micro-sprinkling and microspray	Generally workers are not in the field when irrigating but they may have contact with wetted equipment. Small drops into the air should be avoided	Fruits and harvestable yield of vegetable crops may be contaminated. Less likely for under-tree irrigation with no wind	Not likely to occur except for the under-irrigated parts of the field resulting from low uniformity of water application	Severe leaf damage can occur definitely affecting yields of annual crops but not for irrigation of trees and vines if drops are large enough and jets are oriented to the soil.

7.2.5. Monitoring and control for safe wastewater use in irrigation

Developing a program to promote safe crop production areas should occur alongside and as an alternative to crop restrictions. This can be achieved with a three-phased process (see Westcot, 1997). The first phase is to develop a sound water quality monitoring program that is used to evaluate the existing levels of contamination in the water being used. This includes selection of contamination indicators, establishing field-sampling methods, defining laboratory methods and participating laboratories, selecting field monitoring sites, and then conducting a field water quality monitoring program. The second phase consists of evaluating the water quality data and developing procedures to assess the levels of contamination. The resulting database can be used to define safe production areas and as a basis to control or regulate contaminated water use in vegetable or other high-risk areas. The third phase is developing mechanisms to regulate the use of potentially contaminated water on high-risks crops, so leading to certification programs.

(a) *Monitoring and development of an information database.*
The goal of a water quality monitoring program is to determine spatially how extensive is the contamination of irrigation water and at what level. Results must provide the Authorities with a sound basis for any required follow-up action. The procedure and parameters used for measurement must have national and international recognition and be applicable to the entire country. The following steps should be considered:

1. Selection of observation areas and sites. This may be performed by considering:
   - The availability of data on water quality and water vector diseases.
   - The location of major vegetable and high-risk crop production areas.
   - The location of major population centres near vegetable production areas, namely those located upstream of vegetable production areas or inside the irrigated area.
   - The availability of information characterising the irrigation system and its operation and management.
   - The irrigation methods and crop production practices used in various production regions of the country.
   - The location and capacity of laboratory facilities.
   - Resources available for conducting the sampling and laboratory analyses.
2. Selection of the water quality indicators, which should be:
   - Not disease specific but applicable to several diseases; indicators include those for helminth eggs and bacteria, namely the faecal coliform.
   - Recognised at national and international levels.
   - Used for routine testing and using analytical procedures well known in national laboratories.
   - Able to provide a basis for establishing guidelines and regulations.
3. Choice of analytical methods, which should be reliable, cost effective and well known from national laboratories, and have international acceptance.
4. Selection of laboratories, in terms of certified quality, knowledge on procedures to be used, and distance to the monitored areas.

5. Selection of sampling techniques, including number and frequency of samples, which depend upon the objectives of monitoring indicators selected, and resources available.
6. Selection of field sites. These depend upon:
   - Water sources in the irrigated area.
   - Location of contaminant inputs, - occurring prior to the canal supply or within the irrigation system (primary and secondary contamination, respectively).
   - Crop patterns and cropping and irrigation practices.

(b) *Data assembling and implementation of a database*. Consideration should be given to existing data - geographical, physical, agronomic, irrigation, health and water quality data - as well as to sampling methods, analytical procedures and indicators to be included in the monitoring program.

(c) *Certification, regulation and other policy issues.*

1. Certification may be considered for the quality of products and for the safety of production, which stimulates optimal practices by the farmers.
2. Similarly, when water quality reaches a level where health hazards are not to be expected, certification can be given to the quality of the water.
3. Certification may be given to an irrigated area where standards are met, or to individual farmers.
4. Policy issues include:
   - Benefits associated with certification.
   - Regulations aiming at control of specified contaminants, promotion of improved health standards and irrigation practices.
   - Policies on long-term wastewater use.

7.2.6. Wastewater for aquifer recharge

When soil and groundwater conditions are favourable for artificial recharge of groundwater through infiltration basins (see Section 6 referring to recharge) partially-treated wastewater may be used to recharge the groundwater. The unsaturated or "vadose" zone then acts as a natural filter and can remove essentially all suspended solids, biodegradable materials, bacteria, viruses, and other microorganisms. Significant reductions in nitrogen, phosphorous, and heavy metal concentrations can also be achieved (Pescod, 1992).

When this water has reached the aquifer, it usually flows within it before it is collected. This movement through the aquifer can produce further purification. The soil and aquifer are then used as natural treatment systems, so they are often called soil-aquifer treatment systems (SAT systems). They constitute a low-technology but advanced wastewater treatment system having the advantage over conventional sewage treatment systems that the water is not only well purified but is also stored for later use.

Various types of SAT systems exist. The simplest is when the wastewater is applied to infiltration basins from where it moves down to the groundwater and drains naturally through the aquifer. Another type is recharge with help of pumping wells. The infiltration basins are arranged in parallel strips and the wells are located midway between the strips. Alternatively, the infiltration basins may be located close together and the wells placed in a

circle around them. Pumping creates a water table depression in the area where the water infiltrates, so accelerating the recharge process.

Despite the fact that SAT systems greatly improve the quality of the sewage effluent, generally the quality of the resulting treated water is not as good as that of the native groundwater. In that case, appropriate management has to be adopted for exploiting the aquifer in such a manner that native groundwater may continue to be pumped for uses requiring higher water quality without being compromised by the recharge effluent. This requires groundwater level and quality monitoring using observation wells located carefully throughout the aquifer system.

Sewage water should travel sufficient distance through the soil and aquifer, and residence times in the SAT system should be long enough to produce water of the desired quality. Travel distance and residence time depend on the quality of sewage effluent, the soil types in the vadose zone and aquifer, the depth to the groundwater, and the desired quality of the water.

The infiltration basins for SAT systems should be located on soils that are permeable enough to give high infiltration rates. The soils should also be fine enough to provide good filtration and quality improvement of the effluent, ideally fine sand, loamy sand, or sandy loam soils. Aquifers should be sufficiently deep and transmissive to prevent excessive rise of the groundwater table due to percolation infiltration. Bare soils often provide the best conditions for the infiltration basins in SAT systems. Dense vegetation can hamper the soil drying process and the recovery of infiltration rates, contribute to evaporation losses, and aggravate mosquito and other insect problems. Suspended algae are also detrimental to infiltration rates and tend to increase the pH of the water.

During flooding, organic and other suspended solids in the sewage effluent accumulate on the bottom of the basins, producing a clogging layer. Drying of the basins causes the clogging layer to dry, crack, and therefore re-establishes the infiltration rates. Besides intermittent drying, periodic removal of this material is also necessary.

The main constituent that must be removed from raw sewage before it is applied to any SAT system is suspended solids. Reductions in BOD and bacteria are also desirable, but less essential. In the USA, the sewage used for recharge typically receives conventional primary and secondary treatment. The latter removes biodegradable material, as expressed by the BOD, but bacteria in the soil can also degrade organic material and reduce the BOD. Thus, primary treatment could normally be sufficient. A detailed description on the process involved in removing the sewage constituents in SAT systems is described in the literature (e.g. Pescod, 1992).

7.2.7. Non-agricultural uses of wastewater

Non-agricultural uses of wastewater are less common then those for irrigation. They include (Loudon, 2001) uses in aquaculture, industry, low quality municipal uses, irrigation of recreational areas including golf courses, and for wetlands. The use of wastewater for irrigation of recreational areas is already dealt with above, being included among the higher risk cases that require more stringent water treatment and monitoring. Lower degrees of treatment may be required when wastewater is used in wetlands since these may act as tertiary treatment facilities.

Aquaculture uses of wastewater are quite common in many parts of the World, including use of non-treated effluents (Mara and Cairncross, 1989). As defined by these authors, aquaculture means water farming for fish production, mainly carp and tilapia, and growing selected water crops such as water spinach, water hyacinth, water calthrop and lotus. Human excreta and animal manure are utilised as fertilisers. The use of untreated materials is fortunately decreasing. However, the risk of infection from fish raised in these waters is small since fish is usually consumed after cooking.

Risks associated with wastewater use in aquaculture (Mara and Cairncross, 1989) consist of:

- passive transfer of pathogens by fish and cultivated aquatic macrophytes,
- transmission of trematodes such as *Clonorchis sinensis* and *Fasciolopsis buski*, whose life cycle includes passing through fish and aquatic macrophytes,
- transmission of schistosomiasis, and
- mainly, field workers exposure to infections.

Techniques for minimisation of risks include the cultivation of species that are not eaten raw, to hold shell-fish in clean water to remove excreted organisms (depuration), keeping fish in clean water for 2 to 3 weeks before harvest, the control of schistosomiasis through the control of snails, and the adoption of preventive measures that enable workers to avoid direct contact with wastewater. The use of wastewater resulting from pre-treatment and first stage treatment processes is also to be considered.

Treated municipal wastewater may be used in domestic water supply when separate distribution systems are available as discussed in Section 8.3.9 and 8.5. Uses refer to demand for low quality water such as for toilet flushing and outdoor washing. Treatments usually follow the more stringent standards to prevent infections by direct contact, since direct contact with the water is always possible. However, costs associated with these dual systems are very high and may be justified only for tourist areas and in regions where water is extremely scarce.

New approaches to on-site wastewater treatment and reuse originated at individual households and small communities are reported in Manel (2001). Main uses concern gardening, green spaces and wetland conservation, but also include domestic uses not requiring very stringent water quality.

Industrial wastewaters generally require treatment specific to the industrial processes from which they are produced. They are determined by the chemical composition of the effluents and the reuse objectives. Commonly, the treated effluents are reused in the same industrial plant for uses that do not require high water quality such as cooling, washing and outdoor uses as referred in section 8.6. The degree of treatment is site specific. Generally health risks are not related to pathogens but to toxic ions such as heavy metals.

7.3. Use of brackish, saline and drainage waters

7.3.1. Characteristics and impacts of saline waters

Saline water includes water commonly called brackish, saline or hyper-saline from different

sources, including aquifers which are naturally saline or became saline due to human activities, and drainage effluents from agricultural land. It also includes water that contains one or more specific elements in concentrations above those found in good quality water.

Fresh water is considered to have a total dissolved solids (TDS) concentration of less than 500 mg/l (EC < 0.7 dS/m). Saline and brackish water have 500 to 30 000 mg/l (0.7 to 42 dS/m) TDS, while sea water has TDS averaging 35 000 mg/l (49 dS/m).

The use of saline drainage water in Egypt is above 5 billion m^3 for irrigating nearly 500 000 ha of land. Drainage water is used in many parts of the world including California, USA. Saline groundwater is used extensively in many countries such as Tunisia, India, and Israel. Reports on use of saline water are abundant in the literature (e.g. Kandiah, 1990, Rhoades *et al.*, 1992; Tyagi and Minhas, 1998, Gupta *et al.*, 1998). The use of highly saline waters, unusable by common agricultural crops, may be feasible for halophytes, which could be explored for human and animal consumption (Choukr-Allah *et al.*, 1996; Hamdy and Lieth, 1999).

Waterlogging, salinity and related problems have arisen in many irrigation areas where fresh water is used for irrigation. Such problems could arise even more quickly and more severely when saline water is used. The major potential hazards associated with the use of saline water in agriculture are (Ayers and Westcot, 1985, Kandiah, 1990):

(a) *Yields decrease* due to:

1. Reduced soil water availability to the crop.
2. Reduced soil infiltration rates to such an extent that sufficient water cannot infiltrate to supply the crop adequately.
3. Soil crusting, affecting infiltration of water and crop emergence.
4. Toxicity to the crop when the concentration of certain ions is high enough to cause crop damage and to reduce yields.
5. Imbalance of nutrients available to crops, caused by excess concentrations of certain ions or the prevention of crop uptake of others.

(b) *Soil degradation* up to the point of making it unproductive due to:

1. Salinisation: when saline water is used inappropriately, particularly in the absence of adequate leaching and drainage, salts accumulate in the root zone and in the groundwater from where they rise to the soil surface, so the soil becomes saline.
2. Sodification: when the composition of salts in the saline water is such that there is a relatively high sodium content as compared to other cations, then the soil complex accumulates this excess sodium. When soils become sodic, they lose their structure and tilth, become dispersive and have reduced infiltration rates and permeability.
3. Loss of soil productivity: when the processes of salinisation and or sodification are continued, conditions for plants to extract water and nutrients become progressively worse and soil productivity decreases to levels where crop production is no longer feasible.

(c) The *effects on the environment* are related to specific ions transported in the water, namely, nutrients and toxic elements. Effects include:

1. Soil degradation as referred above, which is an environmental damage by itself and contributes to desertification.
2. Damages to the soil environment, causing negative changes in plant communities which hampers animal life and soil biodiversity.
3. Nutrients in reused drainage effluents give rise to uncontrolled algal blooms, and to heavy development of aquatic weeds in irrigation canals and other water bodies where they discharge. Those lead to clogging problems in hydraulic structures and equipment, in waterways and canals, and reduce the wild life which inhabit farm ponds, lakes and reservoirs.
4. When nitrogen in reused drainage waters is excessive or when it is not taken into consideration in the fertilisers' balance, the resulting excess nitrates add to groundwater pollution.
5. The presence of particular ions to levels exceeding specific health and safety thresholds affect either plants sensitive to those ion concentrations, or animals that drink those waters. A typical case is the presence of selenium in drainage waters in California, which affects certain bird communities, with consequences for the whole of the environmental chain in which they play a part.

(d) The *risk for public health* result from:

1. The presence of toxic ions such as the heavy metals that, although they may be present in minute concentrations, are cancerous when accumulated in humans.
2. Some vectors of disease, such as mosquitoes and snails, which develop better in saline waters, mainly those rich in nutrients, so creating or increasing health hazards for the populations living in areas using saline water or reusing drainage waters.

The negative impacts which result from the use of saline waters can be overcome when water management is performed appropriately, that is having the control of the negative impacts as a main goal. However, this implies good knowledge of the mechanisms influencing plant stress and soil degradation, and appropriate information on the quality characteristics of the waters being used and of the toxic ions, nutrients or disease vectors likely to be present. Only when such information is available will it be possible to select the crops, cultivation techniques, irrigation methods and water management practices that facilitate saline water use.

An FAO expert consultation (Kandiah, 1990) revised the recommendations for use of saline water for irrigation. These include the need for:

- Integrated management of water of different qualities at the levels of the farm, the irrigation system and the drainage basin when sustaining long-term production potential of land and water resources is a main goal.
- Adopting irrigation methods with high performance, using minimal leaching fractions to reduce drainage volumes, implementing reuse of drainage water for progressively more tolerant crops, and reusing otherwise unusable saline water for halophyte production.
- Monitoring of soil and water quality, providing feedback to management to provide for optimal operation and control of the irrigation systems.

- Further development in understanding the effects of saline irrigation water on soil-plant-water relationships, including cumulative effects on perennials.
- Promotion of tools to predict long and short-term effects of irrigation water quality on crop yields, soil properties and quality of the environment.
- Establishment of pilot areas to test and assess irrigation methods and complementary soil and crop management practices for using saline water.
- Training of irrigation and agricultural officers.

7.3.2. Criteria and standards for assessing the suitability of water for irrigation

A great deal of research on the water quality requirements for irrigation has been developed over a long time. Consolidated standards have been made available, namely by FAO (Ayers and Westcot, 1985; Kandiah, 1990; Rhoades *et al.*, 1992). It is then possible to define the main water quality parameters which must be known to allow saline waters to be used safely in irrigation. Recommendations by FAO include:

(a) Water quality characteristics to be considered for irrigation to assess the suitability of saline water concerning, particularly:
   - Salinity hazards (total dissolved salts, TDS and electrical conductivity, EC).
   - Crusting and permeability hazards (SAR or SARadj (also renamed RSC), EC, and pH).
   - Specific ion toxicity hazard (Na, Cl, B, and Se, among others).
   - Nutrient imbalance hazard (excess NO_3, limited Ca, phosphate, etc.).

(b) Parameters required to evaluate the quality of saline water on a routine basis include: TDS, EC, concentration of cations and anions (mainly Ca, Mg, Na, CO_3, HCO_3, Cl, SO_4), SAR or the adjusted SAR (or RSC) under certain conditions, trace elements (such as Se, As, B, Mo, Cd, Cr, Cu), as well as other potentially toxic substances of agricultural origin.

(c) Water quality standards already available should be evaluated through research and adjusted for the specific conditions of saline water use, including soils, climate, crops and crop sequences, and irrigation methods. More emphasis should be given to the development of appropriate models, criteria and standards applicable under non-steady conditions.

(d) Guidelines on use of saline water should also include the possible hazardous effects of trace elements on people or livestock which consume crops produced using such water (As, Se, etc.).

The main water quality characteristics for saline waters are summarised in Table 7.7, with indications of the restrictions on their use in relation to the overall quality of the water. Restrictions mainly concern crop tolerance to salts, need for leaching, specific requirements for the irrigation methods and systems, and soil management practices.

7.3.3. Crop irrigation management using saline water

Water for agricultural use is normally considered to be in one of five salinity classes. These classes are outlined in Table 7.8, their boundaries being defined by the total dissolved

solids and electrical conductivity of the water.

Crop responses to salinity vary with crop species and, to a lesser degree, with the crop variety. The tolerance of crops to salinity is generally classified into four to six groups, from the sensitive (or non tolerant), where most horticultural and fruit crops are included, to the tolerant, which includes barley, cotton, jojoba, sugarbeet, several grass crops, asparagus and date palm. Full lists of crop tolerance classes are given by Ayers and Westcot (1985) and Rhoades *et al.* (1992) among others. A summary of limitations to use of water of different classes and of impacts of salinity on yields in the main crop tolerance groups is given in Table 7.9.

TABLE 7.7. Water quality for irrigation and required restrictions in use (Ayers and Westcot, 1985).

Problems	Water characteristic	No restrictions	Slight to moderate restrictions	Severe restrictions
Salinity effects on water availability	EC (dS/m)	< 0.7	0.7 to 3,0	> 3.0
	TDS (mg/l)	< 450	450 to 2000	> 2000
Salinity effects on soil infiltration	SAR < 3	EC > 0.7 dS/m	EC: 0,7 to 0,2 dS/m	EC < 0,2 dS/m
	3 to 6	> 1.2	1.2 to 0.3	< 0.3
	6 to 12	> 1.9	1.9 to 0.5	< 0.5
	12 to 20	> 2.9	2.9 to 1.3	< 1.3
	20 to 40	> 5.0	5.0 to 2.9	< 2.9
Toxicity	Sodium			
	Surface irrigation: SAR	< 3	3 to 9	> 9
	Sprinkle/spray (me/l)	< 3	> 3	
	Chloride concentration			
	Surface irrigation (me/l)	<4	4 to 10	> 10
	Sprinkle/spray (me/l)	<3	> 3	
	Boron (mg/l)	< 0.7	0.7 to 3.0	> 3.0
	Trace elements	Variable		
Sprinkle/spray irrigation	Bicarbonate (me/l)	< 1.5	1.5 to 8.5	> 8.5
Plant nutrition	pH	Normal 6.5 - 8.5		

TABLE 7.8. Salinity classification of water

	Non saline	Slightly saline	Medium saline	Highly saline	Very highly saline
Total dissolved solids, TDS (mg/l)	< 500	500 to 2000	2000 to 4000	4000 to 9000	> 9000
Electrical conductivity, EC (dS/m)	< 0.7	0.7 to 3.0	3.0 to 6.0	6.0 to 14.0	> 14.0

The behaviour of various crops under irrigation with water of different degrees of salinity varies with species, varieties and the crop growth stages. As irrigation water salinity increases, germination is delayed. Germination is adversely affected for most field crops when the EC of the irrigation water or the soil saturation extract reaches a threshold of 2.4 dS/m. Adverse effects occur at lower values (< 1 dS/m) for non-tolerant crops, and at

higher values for tolerant crops (generally not exceeding 4 dS/m). The germination and seedling stages are the most sensitive to saline water irrigation. Any adverse effects at such stages will lead to a reduction in crop production proportional to the degree of plant loss during germination and plant establishment. At this stage, water of good quality should be used, especially if plants are sensitive. If fresh water is lacking at this stage, irrigation during seedling development, after germination must be carried out with fresh water to avoid dramatic effects on yields (Hamdy, 1996). Besides germination and crop establishment, another growth stage where most crops are more sensitive to salinity is the reproductive phase. Other critical stages vary from crop to crop. Several case studies are reported in the literature (e.g. Hamdy, 1994; Hamdy and Karajeh, 1999).

TABLE 7.9. Summary guidelines for use of saline waters.

Crop tolerance to salinity		Non saline	Slightly saline	Medium saline	Highly saline	Very highly saline
I sensitive	Limitations to use	None	Slight to medium	Restricted	Not usable	Not usable
	Yield reduction	None	Up to 50 %	> 50%	—	—
II moderately sensitive	Limitations to use	None	Slight	Medium	Restricted	Not usable
	Yield reduction	None	Up to 20 %	Up to 50 %	> 50%	—
III moderately tolerant	Limitations to use	None	None	Slight to medium	Medium	Very Restricted
	Yield reduction	None	None	20 to 40 %	40 to 50 %	> 50%
IV tolerant	Limitations to use	None	None	Very slight	Slight to medium	Restricted
	Yield reduction	None	None	Practically none	20 to 40 %	> 50%
Halophytes	Limitations to use	—	—	—	—	Suitable

The suitability of water for irrigation based on salinity, leaching and drainage requirements, and crop tolerance to salinity must be related to irrigation management. Several approaches can be adopted in water and crop management to minimise the accumulation of salts in the active root zone and to eliminate salt stress, especially during the critical growing stages of the plants. These include:

- Appropriate selection of irrigation methods.
- Efficient leaching management, including volumes and frequency, and respective drainage of the salty water away from the cropped land.
- Proper irrigation scheduling, in agreement with the available irrigation system.
- Crop rotations adapted to the prevailing conditions. Considerations must include irrigation water quality, soil salinity levels, chemical and physical properties of the soils, and climatic conditions.

The selection of the irrigation method must consider the quality of the water and the potential for both the water and the irrigation method to produce negative impacts. A summary of the more relevant considerations is presented in Table 7.10. These refer to the capabilities for controlling:

TABLE 7.10. Evaluation of the irrigation methods for use with saline water.

Irrigation method	Salt accumulation in the root zone	Foliar contact, avoiding toxicity	Ability to infiltrate water and refill the root zone	Control of crop stress and yield reduction
Basin irrigation	Not likely to occur except for the under-irrigated parts of the field when uniformity of water application is very poor. Leaching fraction difficult to control in traditional systems	It is possible only for bottom leaves in low crops and fodder crops, and during the first stage of growth of annual crops	Adequate because large volumes of water are generally applied at each irrigation and water remains in the basin until infiltration is complete	Adequate because toxicity is mostly avoided, salts are moved down through the root zone, infiltration is completed and irrigation can be scheduled to avoid crop stress
Corrugated basin irrigation	Salts tend to accumulate on the tops of the ridges. Leaching prior to seeding/planting is required for assuring germination and crop establishment	Exceptionally because crops are grown on ridges.	As for flat basins, above	As for flat basins but depending on avoiding salt stress at plant emergence and crop establishment
Border irrigation	As for basin irrigation but infiltration control is more difficult, as is the control of the leaching fraction	As for flat basins	Because water infiltrates while flowing on the soil surface, runoff losses increase when infiltration decreases	Crop stress is likely to occur due to reduced infiltration, so inducing relatively high yield losses
Furrow irrigation	Salts tend to accumulate on the tops of the ridges. Leaching is required prior to seeding/planting	Exceptionally because crops are grown on ridges	Salinity induced infiltration problems cause very high runoff losses	Crop stress is very likely to occur due to reduced infiltration, so inducing significant yield losses
Sprinkler irrigation	Not likely to occur when set systems are used except for the under-irrigated parts of the field due to low uniformity. Instead, problems occur with equipment designed for light and frequent irrigation	Severe leaf damage can occur affecting yields. Damage greater with more frequent irrigation.	Salinity induced infiltration problems including soil crusting may cause very high runoff losses	Crop stress is very likely to occur due to toxicity by contact of water with the leaves and fruits, and to reduced infiltration, thus significant crop stress and yield losses may occur
Micro irrigation: drip and subsurface irrigation	Not likely to occur except for the under-irrigated parts of the field due to low uniformity, including that resulting from nozzle clogging when water filtration is poor	Not likely to occur	Problems generally do not occur except when there are not enough emitters and under-irrigation is practised	These systems are able to provide for crop stress and toxicity control, so yield losses are minimised
Micro irrigation: micro-sprinkling and microspray	Not likely to occur except for the under-irrigated parts of the field due to low uniformity and clogging; leaching could be then more difficult	Leaf damage can occur, affecting yields of annual crops. Less damage for tree crops	Problems are similar to those for set sprinklers, so runoff losses may be important	Toxicity due to direct contact with the leaves. Non uniform application may produce crop stress and runoff. Yield losses likely to occur

- soil salinity hazards due to salt accumulation in the root zone,
- toxicity hazards caused by direct contact of the salty water with the plant leaves and fruits,
- soil infiltration and permeability hazards caused by the modification of the soil physical properties, mainly due to the Na ion, and
- yield hazards which may occur when the irrigation system does not allow adoption of appropriate irrigation management, the frequency and volumes of irrigation.

One of the most important factors in crop management when using saline irrigation is the irrigation frequency. Saline water requires more frequent irrigation than for fresh water because salts in the water and the soil increase the osmotic potential of the soil water, which makes water uptake by the crop roots more difficult. However, increasing the frequency implies reducing the depth of water applied at each irrigation to avoid gross accumulation of salts in the soil. The irrigation application depths that can be used depend on the irrigation method and the off-farm system delivering water to the fields.

Surface irrigation methods make it extremely difficult to apply small irrigation depths, as outlined in Section 8.8. When water is delivered to the farms through surface canal systems, the delivery schedules are generally of the rotation type, and are rigid, delivering large irrigation volumes at long intervals. These systems are inappropriate for irrigation of less tolerant crops.

7.3.4. Leaching requirements and control of impacts on soil salinity

The leaching requirement is usually computed from (Ayers and Westcot, 1985).

$$LR = EC_{iw} / (5\ EC_e - EC_{iw}) \tag{7.2}$$

where EC_{iw} is the electrical conductivity of the irrigation water and EC_e is the electrical conductivity of the saturated extract of the soil. EC_e should be the average soil salinity tolerated by the crop. This value should not be that for achieving maximum yield but that which will provide an acceptable yield decrease, i.e. for attaining 70 to 90 % of the potential yield.

A methodology for estimating salinity impacts on crop yields is proposed by Rhoades *et al.* (1992), and Allen *et al*. (1998) propose a method for estimating crop water requirements under salinity conditions. These methods rely on knowledge of the threshold EC_e at which crops are affected, and the rate of yield decrease when the salinity of the irrigation water increases by 1 dS/m. These values are tabulated in both quoted publications. The EC_e threshold ranges from 1.0 dS/m for very sensitive crops such as carrots and beans up to more than 7.5 dS/m for barley, cotton, and tolerant grasses. The rate of decrease in yield per unit increase in EC varies from more than 15 % (dS/m) for the sensitive crops down to 5 % (dS/m) for tolerant crops.

When a leaching fraction is applied with the irrigation water the salinity built up of the soil is reduced non-linearly with the size of that fraction. In general this may be expressed by:

$$EC_e = \frac{1 + LF}{LF} \frac{EC_{iw}}{5} \tag{7.3}$$

where LF, the actual leaching fraction, is used in place of the leaching requirement, LR. This equation shows that the soil salinity EC_e increases proportionally to the salinity of the irrigation water, EC_{iw}. The salinity built up can not be prevented by drastically increasing the leaching fraction, because this would dramatically increase the percolation of water, causing the water table to rise, waterlogging and degradation of the quality of the groundwater. Under conditions of water scarcity, this would be a very poor use of the available water. Moreover, the degrading of the quality of local water bodies, surface or groundwater, by adding water of inferior quality would further contribute to the problems of water scarcity. Therefore, depending on the crop, and the salinity of the water and soil, a 15-20 percent leaching fraction is commonly recommended. The equation (7.3) above predicts that $EC_e = 1.5\ EC_{iw,}$ when the salinity of the soil and the irrigation water are in equilibrium. Lower EC_e can be produced if good quality water, including rainwater is employed for leaching. Therefore, the conjunctive use for irrigation of saline water and good quality water is advocated, and similarly for the case of using wastewater for irrigation.

Several strategies are usually adopted to facilitate irrigation with saline water, as reported by Kandiah, 1990; Gupta *et al.*, 1995; Hamdy and Karajeh, 1999 among others. Mainly the strategies consist of:

(a) The *dual rotation* management strategy (Rhoades, 1990), in which sensitive crops (e.g. lettuce, alfalfa) in the rotation are irrigated with low salinity river water, and salt-tolerant crops (e.g. cotton, sugarbeet, wheat, barley) are irrigated with saline drainage water. For the tolerant crops, the switch to drainage water is usually made after seedling establishment, i.e. irrigations at pre-planting and at the initial crop stages are made with low salinity water. Benefits from this strategy include (Rhoades, 1990): (i) harmful levels of soil salinity in the root zone do not occur because saline water is used only for a fraction of the time; (ii) substantial alleviation of salt build-up in the soil occurs during the time when salt-sensitive crops are irrigated with fresh water; (iii) proper pre-planting irrigation and careful irrigation management during germination and seedling establishment leach salts out of the seed layer and from shallow soil depths. The main difficulties with this strategy are the complexity of water management for farmers and system mangers and the possible lack of fresh water when it is required.

(b) *Blending*, which is a drainage reuse strategy where water supplies of different salinity levels are mixed in variable proportions before or during irrigation (Shalhevet, 1994; Rhoades, 1990, Tyagi, 1996). Irrigation water having a quality superior to that of the saline water and able to satisfy the allowed salinity threshold for the crops to be irrigated is obtained. Blending may be more practical and appropriate on large farms because it is practised by the farmer himself, taking into consideration the crops grown and the respective growth stages. On the other hand, in large irrigation systems supplying many small farms it would be difficult to properly satisfy the requirements of all the crops to be grown, unless a cropping pattern was imposed for all farms.

(c) *Cyclic application* of saline and fresh water (Tyagi, 1996). Salinity must not be above acceptable thresholds for the crops grown. Cycles of application of fresh water should coincide with the more sensitive growth stages, particularly for planting and seedling development, and for the leaching of the upper soil layers. This strategy has more

potential and flexibility than the blending strategy and may be easier to implement.

7.3.5. Long-term impacts. Monitoring and evaluation

Most studies indicated that using irrigation water containing salts in excess of conventional suitability standards, can be successful on numerous crops for at least seven years without a loss in yield (Rhoades, 1990). However, uncertainty exists concerning the long-term effects of these irrigation practices on the physical quality of the soil. These effects largely depend on the soil chemical and physical characteristics, on the climate and on the possibility of leaching with natural rain or using higher quality water for leaching as mentioned above.

The greatest concern with regard to long-term reuse of drainage water for irrigation is its effects on the soil physical quality, particularly the reduction of water infiltration capacity. According to Rhoades (1990), this is especially important where reuse is practised on poorly structured soils and the drainage water has SAR > 15 (mmol/l)½. The capability to predict changes in soil infiltration and permeability is still beyond current knowledge of soil physics.

Long-term effects on soil salinisation are already considered when using simulation models. However existing knowledge is quite limited. Soil variability in space and irrigation variability both in time and space produce large uncertainty in predictions. For instance, soil salinity under a cyclic strategy of application will fluctuate more, both spatially and temporally, than if using a blending strategy. Therefore, predicting or anticipating plant response would be more difficult under the former. Nevertheless, management schemes must be practised that keep the average root zone salinity levels within acceptable limits in both strategies.

Drainage water often contains certain elements, such as boron and chloride, that can accumulate in plants to levels that cause foliar injury and a subsequent reduction in yield. This is another cause of uncertainty and, in many cases, this may produce more long-term detrimental effects than salinity. Another long-term consideration with regard to reuse of drainage water is the potential for accumulation of heavy metals in plants and soils. These metals can be toxic to human and animal consumers of the crops. For these cases also, there is only limited potential for using prediction models to estimate when long term impacts would be important.

Monitoring soil salinity, leaching and drainage adequacy is therefore required to evaluate the long term impacts from using saline waters, irrespective of whether the source of the saline water is groundwater or drainage water. Monitoring and evaluation should be concerned with:

- The status of salts throughout the soil profile on a continuous basis, with the aim of detecting changes in salinity levels and identify when salt build up is steadily increasing.
- The functioning and performance of the drainage system, including observations of the hydraulic head, drainage outflows and salts transported with the drainage water.
- The irrigation performance, not only to observe the irrigation efficiency but also the uniformity of water distribution and the leaching fractions actually applied.
- The irrigation schedule in respect to the satisfaction of irrigation and leaching

requirements, and the constraints on delivery or other restrictions that may hamper the appropriate irrigation management.

- Sampling EC throughout the irrigated area to identify the occurrence of problem areas requiring specific care in water management.
- Sampling for specific ions that may be present in the irrigation water and that could have specific toxicity effects or, as for heavy metals, could create health risks.
- Follow-up non agricultural impacts from using saline water, such as changes in groundwater quality, in plant ecosystems and in wetland or river-bed fauna and flora.

Traditional laboratory techniques of salinity measurement using soil samples are impractical for the inventory and monitoring requirements of large areas, so new approaches have recently been developed, particularly those described by Rhoades *et al.* (1999) that were developed especially for application in large areas. Environmental impact assessment methodologies for irrigation and drainage projects (Dougherty and Hall, 1995) may also be adapted for surveying and monitoring areas where water of inferior quality, i.e. saline and wastewater, is used for irrigation.

7.3.6. Non-agricultural use of saline waters

Non-agricultural uses of saline waters are quite limited. Domestic water uses are traditional in areas where fresh water is not available for small villages and isolated households. Low salinity brackish water may then play a major role. However, these waters are not appropriate for drinking nor for animal consumption, and thus conjunctive use of this water with high quality water, for example from roof-top collection, is required.

For large populations, when a separated municipal distribution system is available, brackish saline water may be used for low quality demanding uses such as toilets and washing, similar to what was discussed for wastewater reuse (7.2.7). However, saline waters have an advantage over treated wastewaters in that they tend to be free of pathogens. However the presence of salt and its corrosive potential may affect the piping system and the equipment where it would be used. Therefore, as for treated wastewater, its use is only recommended when water of good quality is definitely insufficient to satisfy the demand, such as during peak periods. The cyclic use of good quality water for flushing salts accumulated in the pipe systems is then recommended. For the above reasons, the use of saline waters in industry is very limited.

Saline and brackish water can also be used in outdoor facilities since it is free of pathogens. However, it may be less appropriate for irrigation because lawns and most garden plants are not salt tolerant. Advice provided above for irrigation of agricultural crops could be followed for ornamentals but little is known of the response to salts of most of the commonly used flowers, shrubs and trees. Nevertheless, landscapes may be planned with plants known to have some degree of tolerance to salinity.

7.4. Desalinated water

7.4.1. General aspects and treatment processes

Seawater and brackish water desalination is progressively being used by more countries in their effort to cope with water scarcity. This is especially accentuated by the growth of urban areas, and the development of arid areas and tourism.

Desalination is a water treatment process that removes salts from saline water to produce water that is low in total dissolved solids (TDS). The use of this process in areas of water scarcity has obvious benefits, whether ocean water or brackish inland water is used. Quite a number of different desalination processes can be applied but in practice, only a limited number of them are economically viable. The various processes considered here are distillation, electrodialysis, reverse osmosis and solar desalination. An updated review of desalination is presented by Semiat (2000).

A desalination plant can be pictured as a black box into which feed water and high-grade energy are fed and from which low grade energy, brine and desalinated water are produced. The TDS of the feed water may range from 500 to 50 000 mg/l. The feed water must be treated to the level for which the plant was designed before it is fed into the plant itself. This treatment may include physical filtration, chemical conditioning and other. The desalinated water produced by the plant is usually in the range of 50 to 500 mg/l TDS and to be used for human consumption must at least comply with WHO limits (Table 7. 11).

The energy input into desalination plants is usually thermal, electrical or mechanical and very often is a combination of all these. Energy rejection from the plants is usually low-grade (thermal) energy. To be able to assess the performance of a desalination plant two important parameters are used - the recovery ratio (R_c) and the performance ratio (R). R_c is defined as the ratio of the product water to the feed water while R is the reciprocal of the energy consumption.

TABLE 7.11. WHO (1995) and EEC (1999) guidelines for quality of water intended for human consumption.

	EEC Max Allowed Concentration	EEC Guideline	WHO Guideline
Chloride Cl^- mg/l	250	25	250
Sulfate $S0_4^-$ mg/l	250	25	250
Fluoride F^- mg/l	1.5		1.5
Nitrates $N0_3^-$ mg/l	50	25	50
Magnesium Mg^{++} mg/l	50	30	125
Potassium K^+ mg/l	12	10	
Sodium Na^+ mg/l	200	20	200
Iron Fe^{++} mg/l	0.2	0.05	0.3
Zinc Zn^{++} mg/l		0.1 / 5.0**	3.0
Copper Cu^{++} mg/l	2.0	0.1 / 5.0**	2.0
Lead Pb^{++} mg/l	0.01		0.01
Calcium Ca^{++} mg/l		100	
Phenols mg/l	0.0005		0.001
Total Dissolved Solids* mg/l	1500		1000

* This parameter is actually total dissolved and suspended solids.
** Values for running/stagnant water sample.

The main desalination processes are:

(a) *Thermal Distillation (TD).* When a saline solution is boiled, the vapour that comes off is pure water and when this is cooled (condensed) the resulting water is found to contain no salt. This separation is perfect and the fact that the vapour separates very easily makes this very old method of desalination popular. The main drawback is that the energy required to evaporate a saline solution is quite high because of the high latent heat of vaporisation of water. For this to be done economically in a desalination plant, the boiling point is altered by adjusting the atmospheric pressure on the water being boiled to produce the maximum amount of water vapour under controlled conditions. The temperature required for boiling water decreases as the pressure above the water decreases. The reduction of the boiling point is important in the desalination process for two major reasons: multiple boiling and scale control. These two concepts, boiling temperature reduction and multiple boiling, have made various forms of distillation successful in locations around the world. Three types of thermal distillation units are used commercially; namely, Multistage Flash (MSF); Multiple Effect Distillation (MED); and, Vapour Compression (VC).

(b) *Electrodialysis (ED).* If a current is passed through a saline solution the different ions (cations and anions) in the solution will carry the current from one electrode to the other by drifting in opposite directions. If an ion selective membrane is placed in this flow, say an anion permeable membrane, only the anions will manage to pass through. If an alternating series of cation/anion selective membranes are placed in the path of the ion flow, the channels formed between the membranes will alternately become concentrated and diluted. The overall effect is that salt is being removed from every alternate channel to its neighbouring channels. The basic ED unit consists of several hundred-cell pairs bound together with electrodes on the outside and referred to as a membrane stack. Feedwater passes simultaneously through the cells to provide a continuous, parallel flow of desalted product water and brine that emerge from the stack. ED is only an economical process when used on brackish water, and tends to be most economical at TDS levels of up to 4 000 to 5 000 mg/l. ED units have a waste discharge of brackish water ranging in volume from 10% to 50% of its output of freshwater. The feedwater must be pre-treated to prevent materials from entering the membrane stack that could harm the membranes or clog the narrow channels in the cells. Post-treatment consists of stabilising the water and preparing it for distribution by removing gases such as hydrogen sulphide and adjusting the pH.

(c) *Reverse Osmosis (RO).* This is a membrane separation process in which the pressure of the water is raised above the osmotic pressure of the membrane. No heating or phase change is necessary for this separation, and the major energy requirement is for pressurising the feedwater. In practice, the saline feedwater is pumped into a closed vessel where it is pressurised against the membrane. As a portion of the water passes through the membrane, the salt content of the remaining feedwater increases. A portion of this saltier feedwater is discharged without passing through the membrane. RO units have a waste discharge of brackish water or brine which could range from 35% to 100% of its output of fresh water, depending on the feedwater being treated. Two improvements have helped reduce the operating costs of RO plants during the past decade. These are the development of membranes that can operate efficiently at lower pressures and the use of energy recovery devices.

(d) *Solar Desalination (SD).* There are three basic ways in which solar energy is used to desalinate saltwater. These are humidification, distillation, and photovoltaic separation. Solar humidification imitates a part of the natural hydrologic cycle by using the Sun's rays to heat a saline water source to produce water vapour. This vapour, or humidity, is then condensed on a cooler surface and the condensate collected as product water. In the solar distillation process, a solar collector is used to concentrate solar energy to heat the feedwater so that it can be used in the high temperature end of a standard thermal desalination process. This is usually a multiple effect or multistage flash process. These units tend to be very capital intensive and require specialised staff to operate them over a long period of time. In addition, they require additional energy inputs to pump the water through the process. Desalination with photovoltaics use photovoltaics to provide electrical energy to operate standard desalting processes like reverse osmosis or electrodialysis. Batteries are used to store energy and inverters are needed to supply alternating current when necessary. The availability of solar energy for only part of the day requires commercial units to be oversized to produce the quantity of water required.

7.4.2. Extent of use and costs of the various desalination methods

Distillation accounts for about 65% of the worlds installed desalination capacity, with the MSF process making up the highest proportion of distillation units. The MSF and MED processes are often used as part of a dual purpose facility where the steam to run the desalination unit is taken from the low pressure end of a steam turbine that is used to generate electricity. The remaining steam and condensate is then returned to the boiler to be reheated and reused. Individual MSF or MED units generally have a capacity of 1000 to 20000 m^3/day but several of these units can be grouped around an electrical generating plant. Facilities with a total water output of 200000 m^3/day or more are not uncommon in the Middle East, while smaller facilities, consisting of several 5000 m^3/day units, are common. VC units are also widely used but, individually, these have much smaller capacities, and, hence, a lower overall total capacity than that of the MSF and MED plants.

Electrodialysis makes up about 5% of the world's installed desalination capacity. Electrodialysis units are used in applications requiring smaller volumes of water and can be purchased in units with individual capacities ranging from 10 to 4000 m^3/day.

Reverse osmosis makes up about 30% of the worlds installed desalination capacity. RO units are also small relative to thermal distillation units, and can be purchased in units with individual capacities from 10 to 4000 m^3/day. The largest plants are in the range of 40000 m^3/day made up of a number of 2000 m^3/day individual units. RO plants include a 20000 m^3/day plant in Malta for seawater desalination, commissioned in 1983 and producing in 1986 about 30% of the island's total water supply; a 30 000 m^3/day plant on Gran Canaria which supplements the water supply of the capital; in Cyprus, a 40000 m^3/day plant was commissioned in 1997 and a new plant installed in 2001 produces 51000 m^3/day desalinated from seawater, meeting about half the domestic water supply demand of the island. Other smaller plants are located on a number of islands around the world.

Solar desalination is not used extensively and remains largely experimental. There are no large-scale installations, generally because of the large solar collection area requirements, high capital cost, vulnerability to weather-related damage and complexity of

operation. More than 100 plants are listed in over 25 countries with capacities of less than 20 m^3/day.

The capital cost of the MSF and MED distillation units tends to be in the range of \$1000 to \$2000/m^3/d of installed capacity, exclusive of the steam supply and site preparation. The capital cost for VC units tends to be around \$2500 to \$3000/m^3/d of installed capacity. These units require less site preparation. In general, production costs tend to be in the range of \$1 to \$4/m^3/d of water produced, depending on the size of the unit. The 1995 capital cost of electrodialysis units tended to range from \$250 to \$750/m^3/d of installed capacity, exclusive of the site preparation, buildings, and development of the raw water supply. Production costs, including depreciation, tended to be in the range \$0.25 to \$1/m^3/d of water produced depending on the size.

The capital cost of brackish water reverse osmosis units ranges from \$250 to \$750/m^3/d of installed capacity, exclusive of the site preparation, utilities, buildings, and development of the raw water supply. The capital cost of a seawater RO unit could range from \$800 to \$1250/m^3/d of installed capacity. Production costs for a brackish water plant, including depreciation, range from \$0.25 to \$1/m^3/d of water produced, depending on the size. Similarly, for a seawater plant, production costs could range from \$1 to \$4/m^3/d. Table 7.12 lists some recent prices from International Tenders/Contracts for seawater RO desalination plants for privatised water supply i.e. adopting the Build Own Operate Transfer (BOOT) project approach. The dramatic reduction of prices is obvious.

Since there is limited commercialisation of solar units, the capital cost and operating cost are not as well established as for the other processes. The economics of operating photovoltaic, solar desalting units tend to be related to the cost of producing energy with these alternative energy devices. The capital cost of an 80 m^3/d solar-assisted MED facility installed at Umm Al Nar in Abu Dhabi has recently been estimated at about \$2 million, or about \$25 000/m^3/d of installed capacity.

TABLE 7.12. Seawater R.O Desalination. Trend in Costs from International Tenders/Contracts*.

Capacity (m^3/day)	Location	Country	Year	Notes	Tender price (USD/ m^3/d)
3500	Galdar	Spain	1988	Common Site Mobilization	1,943
10000	Suresle	Spain	1990		1,622
10000	Galdar	Spain	1990	Common Site Mobilization	1,336
25000	California	USA	1990		1,458
20000	Dhekeleia	Cyprus	1990	First Tender, Invalidated	1,472
20000	Dhekeleia	Cyprus	1995		1,220
10000	Bahamas	Bahamas	1995		1,254
8000	St. Maarlen	NL Antilles	1995		1,690
11000	Canary Island	Spain	1995	Estimated for 1/3 Expansion	1,184
150000	Florida	USA	1996	Budgetary for Tender File	1,039
45000	Las Palmas	Spain	1996	Under Turnkey Contract with O/M Cost Duty	1,027
56000	Marbella	Spain	1996	Variable up to 1,100	1,000
40000	Larnaca	Cyprus	2000	Tenders	0,840
20000	Limassol	Cyprus	1999	Tenders	0,660

* DuPont Regional Office, Athens 1996 except for the last two entries.

7.4.3. Seawater desalination: the Cyprus experience

Cyprus is an island with a semi-arid climate. Its water resources are intensely utilised and it is suffering from structural and temporary water shortages. During the last ten years the available water from Government projects and from other sources was very limited, which led to supply cuts of up to 30% of normal demand in the domestic sector and up to 70% of the normal demand in the agricultural sector. These have serious adverse effects on the social and economic activities and a negative impact on the environment. In order to cope with the water scarcity, the Government of Cyprus has decided to construct a number of desalination plants. The target capacity of these plants will be 120,000 m^3/d or 40 million cubic metres per year with the objective of increasing water availability and the level of reliability for domestic water supply systems. The first desalination plant was commissioned in April 1997, with a nominal output of 40,000 m^3/day, whilst the second desalination plant with a nominal output of 51,667 m^3/day started operating in May 2001.

Both plants use the RO process with a recovery of 50% and energy from the Electric Power grid. They both use an open sea intake and the water is undergoing a pre-treatment for reducing the silt density index and the pH for the protection of the membranes. The desalinated water is post-treated for achieving an acceptable quality complying with the Cyprus and European drinking water quality standards. The BOOT principle was chosen as the method of project financing on a ten-year basis. The desalinated water is presently sold to the Government, at source, at a varying unit price, about US$ 0.85/m^3 for the plant commissioned in 1997 and US$ 0.68/ m^3 for the plant that was put in operation in 2001.

Undoubtedly, the discharge of brine impacts the marine environment. At the Dhekelia plant in Cyprus (40 000 m^3/d), the discharge of brine with a salinity of 72 $^0/_{00}$ through an outfall which ends at a multi-point diffuser, at a depth of about 5 m and at a distance of 250 m from the shore, resulted in an increase in salinity within a distance of 200 m from the point of discharge. The sea environment around the brine disposal point is monitored on a continuous basis and the results so far are at acceptable levels. In all cases, environmental impact assessment studies were carried out before construction and mitigation measures were imposed on the contractors for minimising adverse environmental effects.

7.5. Fog-capturing, water harvesting, cloud seeding, and water transfers

Dew, mist and fog generally make only a small contribution to precipitation in water scarce regions. However, they can be responsible for peculiar vegetation ecosystems in arid or semi-arid areas. Several physical processes influence the occurrence of these ecosystems. Agnew and Anderson (1992) refer to the importance of fogs in several coastal areas in Namibia, Oman and Peru.

Fog collection is used in isolated arid areas, in mountains and islands where the occurrence of fog is common but rainfall is rare. Ancient examples of fog capturing have been found in the Negev, the so-called “dew mounds”, and in Crimea, these ones constituted by piles of rocks named “aerial wells” (NAS, 1974). Modern examples are reported by Agnew and Anderson (1992) for Peru, Oman and the Negev. Several case studies are described in Schemenauer and Bridgman (1998), namely the use of fog collectors in Chile and Peru coastal villages and in the islands of Cape Verde, located

offshore of the Sahel zone of Africa, fog-harvesting in Namibia, Oman, The Negev and Canary Islands. Particular attention is given to the chemical composition of fog water in view of its use by humans, animals and ecosystems in dry areas (Schemenauer and Bridgman, 1998).

Fog capturing is achieved by means of appropriate screens that favour the coalescence of the small fog droplets to create larger drops with enough dimensions to flow down by gravity into collectors. Fog screen collector design is described by Cruzat (1998). The amount of water collected every day is small and depends on the properties of the air masses passing over the collection sites. The reliability of fog capturing is associated with the frequency of fog occurrence. When fog occurs nearly everyday, a water yield of 3 $l/day/m^2$ of collector net may occur as in Mexico. In general, fog capturing is only feasible for human consumption for small populations living in such areas, and for drinking of animals, mainly those grazing on high pasture lands where frequent fogs favour vegetation despite the lack of rains. Reviews of fog capturing by natural vegetation and its impacts on ecosystems in dry African regions are presented in Schemenauer and Bridgman (1998).

Rainwater harvesting, or simply water harvesting (WH), has been practised for millennia in the Negev and in Petra, Jordan, by the Nabateans. Prinz (1996) refers to water harvesting structures in Jordan from 9000 years ago and in southern Mesopotamia as early as 4500 BC. Rainwater collection was a common practice in the Roman cities of North Africa and the Near East. Water harvesting for agriculture is an ancient practice common in Mexico, Tunisia, the Arabian Peninsula, Afghanistan, Pakistan, India and the Sahel countries, among others. New developments are being introduced in areas where WH was not traditional such as the arid Northeast Brazil, or where social changes require new approaches, such as the Sub-Saharan Africa (Reij and Critchley, 1996).

Roof-top rainwater harvesting, commonly associated with water collection from impermeable areas surrounding the households, plays a major role for making water available for domestic uses and animal drinking in a large variety of rural environments throughout the World. However, care is required to keep stored water in cisterns free from contamination by animals and sewage water. Drinking water has to be boiled before consumption and filtering is commonly also required.

WH for animal drinking is commonly achieved by collecting runoff into small reservoirs created by excavation or using small earth dams. Animals should not have direct access to the stored water to avoid contamination by excreta. Appropriate drinking facilities should be used such as drinking fountains connected to the reservoir by a pipe.

WH for crops varies from one region to another according to the indigenous knowledge, the land form, the soil type, the runoff intensity and the crops to be irrigated. Generally, distinction is made among: inter-row WH, where water collection is made in the location where it is used; micro-catchments WH, where rain is collected in part of the area and is infiltrated in the downstream cropped zone; macro-catchment WH, where runoff water is collected in large areas to be stored in earth dam reservoirs or tanks to irrigate the downstream fields; and floodwater diversion systems, also called spate irrigation systems, where appropriate structures in the river bed divert the flood runoff in a controlled manner to the nearby cropped fields. Runoff WH is discussed in Section 5.4. A selected bibliography on water harvesting is included at the end of this chapter.

Another traditional process for capturing water in arid zones is groundwater harvesting. This term is used to make a distinction from modern groundwater exploitation, which is mainly with tube wells (see chapter 6). It includes dug-wells, which capture quite shallow groundwater and keep being the basic water supply system in many arid or semi-arid areas of Africa and West Asia, horizontal hand made wells, which are commonly in use in many parts of the world, and the qanats. The latter are horizontal tunnels that tap the water in an alluvial fan and transport it to the surface where it is used without any pump or other lifting equipment. The qanats are a heritage of the Persians, who developed them about 3000 years ago. Qanats are used for irrigation in arid zones of Iran, Pakistan, Afghanistan, Xinjiang in West China, the Arab Peninsula, and North Africa. Water is transported underground for several kilometers, in many cases 10 to 20 km. Qanats are composed of dug or horizontal wells for capturing the water, a tunnel having a series of vertical shafts used for digging out the excavation debris and for respiration, and the downstream diversion structures that provide for the distribution of waters into different canals. Qanat systems are of great importance. Modernisation of these systems is desirable but careful approaches have to be used, regarding both the structural and the management aspects. A recent analysis on qanats in Oman, locally called aflaj, is provided by Al-Marshudi (2001), who pays particular attention to the traditional organisational aspects as a key for maintenance and operation.

Weather modification has been an objective of research for a long time but successes reported in the literature is limited. Essentially it consists in using aircrafts to bomb the clouds passing over an arid area with substances such as ice, frozen carbon dioxide and silver iodide, which may serve as nuclei for condensation and coalescence of rain drops. When large enough these drops could fall to the ground. This method for rainfall augmentation is called cloud seeding.

Results show that wet air masses must be cold enough that the formed water particles are in the form of ice crystals that coalescence to be large enough to create drops which can reach the ground as rain. In most low-lying arid areas, wet air masses are not as large, cold or frequent as in mountainous areas. There, cloud seeding could be effective, but these are often unpopulated regions and benefits to the populations can result only from augmentation of runoff due to that increased rainfall. Nevertheless, as reported by Khouri *et al.* (1995), during the 1980 drought in Morocco, cloud seeding over the Atlas mountains increased the rainfall by 10 to 15 %, which caused runoff that could be stored in small dams downstream, and contributed to alleviation of the drought.

Water transfers from one basin to another have not been discussed much until recently. The idea is mostly concerned with long distance transfer of water from basins in a humid or semi-humid zone to another basin in a semiarid environment. A typical example is the Grand Canal in China, for which construction started in the Qin Dynasty, around the year 400 B.C. Its main purpose was navigation but it also served to transfer water from the Yangtse River to the north across the lower reaches of the Yellow River and the Huai River. New water transfers are currently planned to import water from the Yangtse basin to the municipal areas of Beijing and Tianjin and for irrigation and municipal uses in the lower Yellow River and Huai River basins. One of these projects is essentially an update of the Grand Canal system but focuses on the South to North Water transfer.

Several water transfer projects are operating in various parts of the world. This is the

case for the Tajo – Segura transfer from Central Spain to the semi-arid south (Mendiluce, 1986); the Basento – Bradano system in south Italy (Beomonte and Nery, 1986); the transfer of water from the Colorado river to irrigate the arid southern California and to supply the Los Angeles and San Diego areas, and in Western Australia the 700 km pipeline that transports water from south of Perth to Kalgoorlie. Another example is the Snowy Mountains Scheme in Australia, where the coastal flowing Snowy river water is turned inland to provide for irrigation and generate hydropower. In this case power generation pays for the works and irrigation water is put into the inland rivers at no net cost.

Although water transfer is a rational way for increasing water availability in areas where water scarcity is evident or demand largely exceeds the available supply, several factors contribute to a decline in interest in water transfers. They may contribute to an unbalanced regional development since the excess demand in the water importing area may not be fully in balance with its overall ecological potential. Similarly the water exporting region may do not receive all the investments and policy measures that could help it to develop better. These issues are of course questionable, but they give rise to political, cultural and social attitudes opposed to inter-basin water transfers. More important are the recognisable environmental impacts on the basin from where water is transferred due to the consequent decrease in river flow, particularly during the low-flow period, with detrimental effects on the river ecosystems and biodiversity. The environmental impacts in the water importing areas due to quick growth of irrigation areas, urbanisation, and other activities that affect the fragile ecosystems in the water scarce regions may be less evident, but they occur. Finally, costs associated with inter-basin transfers are very high because distances to be covered are large, compensatory measures are costly and environmental control measures are quite demanding. Water transfers are usually only feasible when the water transferred has high value, such as for large population survival and high value industry. Appropriate evaluation and implementation of measures that provide for the sustainable development of both the areas exporting and importing water are required. Yevjevich (2001) presents an updated discussion on these matters. Water transfers should go together with the implementation of water conservation and saving measures since the corresponding increase in availability does not turn the importing area into one of water abundance.

In many areas, the reallocation of water rights may be an alternative or a complementary measure to water transfer (Schaak *et al*., 1990). This reallocation generally relates to the water value and may be easily performed when a water market can be implemented.

8. Water conservation and water saving practices and management

8.1. Importance of water conservation and water savings in coping with water scarcity

8.1.1. Water conservation and water saving

The terms water conservation and water savings are generally associated with the management of water resources under scarcity. However, these terms are often used with different meanings in accordance with the scientific and technical disciplines or the water user sector considered. Very often, both terms are used as synonymous.

The term water conservation is used when referring to every policy, managerial measure, or user practice that aims at conserving or preserving the water resources, as well as combating the degradation of the water resource, including its quality. Water saving aims at limiting or controlling the water demand and use for any specific purpose, including the avoidance of water wastes and the misuse of water. In practice both perspectives are complementary and inter-related. Despite not being easy to distinguish between them, these terms are not used synonymously. In particular, questions relative to preservation and upgrading of water quality are considered as water conservation.

In other sections of this chapter, like in other chapters of this book, different facets of water conservation and water savings are analysed, described and proposed for adoption. Thus, it looks appropriate to first review some of most important aspects of those measures and practices used to cope with water scarcity. These measures and practices are summarised in Tables 8.1 and 8.2 for water conservation and water savings respectively. The tables refer to their relative importance for coping with the water scarcity regimes identified in Chapter 2. In the following sections those measures and practices which have much in common concerning their application to those water scarcity regimes are analysed, focusing on the peculiarities of each one of them.

This chapter analyses with some detail the measures and practices that can be applied by the different user sectors - urban systems, domestic water uses, landscape and recreational uses, industrial and energy, and agriculture, both dryland and irrigated agriculture - to reduce both the water demand and the water consumption, as well as to improve the efficiency in the use of water. These measures and practices constitute guidelines for establishing local, regional or national programmes for water conservation and saving in the different water use

TABLE 8.1. Water conservation measures and practices and their relative importance to cope with different water scarcity regimes

Water conservation measures and practices	Aridity	Drought	Desertification and water shortages
(a) Meteorological and hydrological information networks to support planning and real time operation and management of reservoirs and water supply and irrigation systems	H	H (drought watch systems)	H
(b) Storage and regulation reservoirs for improved availability of the water resources	H	H	M
(c) Land and water use planning and management	H	L	H
(d) Enforcing water quality management measures and practices,	H/M	L	H
(e) Improved conditions for operation, maintenance, and management of water supply systems,	H/M	H	M
(f) Maintenance of required discharges for ecological purposes in natural streams and water bodies	H	L	H
(g) Controlling ground-water withdrawals, recharge and contamination	H/M	L	H
(h) Enforcement of water allocation policies focusing on the prevalent water scarcity problems	H	H	H
(i) Augmentation of available water resources through the re-use of treated waste-waters, drainage and low quality waters, for specified uses	H	H	M/L
(j) Exploring non-conventional water sources by households, farmers, industry and water supply bodies	H/M	H	L
(k) Adoption of water technologies and practices by the end users for resource conservation	H	H	H
(l) Development of soil and water conservation practices in rainfed and irrigated agriculture	H	H	H
(m) Erosion control and soil conservation,	M	L	H
(n) Development of soil and crop management practices for restoring the soil quality,	M	L	H
(o) Combating soil and water salinisation	H	L	H
(p) Development of participative institutions to water management, including legal and regulatory measures	H	H	H
(q) Application of water pricing and financial incentives that favour efficient water uses, and treatment, re-use and recycling of the water,	H	H	H
(r) Adoption of penalties for water wasting and misuse, and degradation of the resource	H	H	H
(s) Enhancing public awareness of the economic, social and environmental value of water, including nature conservation	H	H	H

H = high to very high importance; M = important but not having first priority; L = important but having low priority

TABLE 8.2. Water saving measures and practices and their relative importance to cope with different water scarcity regimes

Water saving measures and practices	Aridity	Drought	Desertification and water shortage
(a) Control of evaporation losses from reservoirs,	H/M	H	L
(b) Control of leaks from canals and conduits,	H/M	H	L
(c) Control of spills from canals and other hydraulic infrastructures,	H/M	H	L
(d) Exploring information systems for decision makers, water system management and improved water uses ,	H	H (drought watch systems)	H
(e) Implementing reservoir and ground-water management rules,	H	H	H
(f) Enforcing water scarcity oriented water allocation and delivery policies	H	H	H
(g) Adoption of reduced demand crops, cropping patterns, cultivation practices, and irrigation techniques,	H	H (drought tolerant crop patterns)	H
(h) Cropping and irrigation practices oriented to control non-point source pollution by agro-chemicals, fertilisers and erosion sediments	M	L	H
(i) Adoption of deficit irrigation practices	M	H	M
(j) Adoption of irrigation and drainage practices favouring salinity management	M	L	H
(k) Adoption of farm water storage and soil water conservation practices	H/M	H	H/M
(l) Use of inferior quality water for irrigation	H/M	H	L/M
(m) Water recycling in industry and in energy generation	H	H	L/M
(n) Adopting water saving tools and practices for reducing domestic, urban, and recreational water uses	H/M	H	L/M
(o) Water price policies in relation to the used water volumes, the specific uses, and the productivity of water use,	H	H	H
(p) Incentives for reducing water demand and consumption	H	L/M	H
(q) Penalties for excessive water uses as well as for low quality effluents and return flows, and	H	H	H
(r) Education and campaigns for adoption by end-users of water saving tools and practices.	H	H	H

H = high to very high importance; M = important but not having first priority; L = important but having low priority

sectors, focusing on the aspects and issues that are more relevant to the areas under consideration. An example of potential application of these guidelines is the program for efficient water use developed for Portugal (LNEC/ISA, 2001), which was developed in parallel to this chapter and followed the approach described here but focusing on the problems and issues more relevant to that country.

8.1.2. Water conservation and water saving to cope with aridity

When aridity is the cause for water scarcity, as analysed in chapter 2, the stress on the natural resources, the vulnerability and fragility of the ecosystems, and the strong inter-sectorial competition for water require that resource conservation policies be enforced. *Water conservation for coping with aridity* (see Table 8.1) could then be considered under several approaches:

(a) exploring meteorological and hydrological data collection and information networks to support planning and real time operation and management of reservoirs, and water supply and irrigation systems,

(b) storage and regulation reservoirs for the augmentation of the available resource for economic and social uses of the water,

(c) maintenance of required discharges for ecological purposes in natural streams and water bodies for conservation of water and riparian ecosystems, and/or protection of normally dry stream-beds in arid and semi-arid regions from actions that will contaminate or in some way reduce the passage of the occasional flows to downstream water users

(d) controlling ground-water withdrawals, recharge and contamination,

(e) improving maintenance, regulation and control of water supply systems for safe operation and higher service performances,

(f) enforcement of water allocation policies that take into consideration the social, economic and environmental uses of the water, as well as their effectiveness in preserving the natural resources and the environment,

(g) augmentation of available water resources through the re-use of treated waste-waters and the use of drainage and low quality waters for specified uses,

(h) adoption of water technologies and practices by the users that provide for resource conservation in terms of quantity and quality,

(i) encouraging households to capture some of their own water e.g. roof water to be stored in a tank or cistern

(j) development of participative institutions for water management, including legal and regulatory measures,

(k) application of water pricing and financial incentives that favour efficient water uses, re-use and recycling of the water, and the treatment of the effluents and return flows, as well as penalties when degraded effluents and return flows are added to good quality surface- and ground-water, and

(l) augmenting the public awareness on the economic, social and environmental value of the water, including for nature conservation.

When water scarcity is due to aridity, *water saving programmes* (Table 8.2) may assume several facets such as:

(a) control of leaks from canals and conduits,

(b) control of spills from canals and other hydraulic infrastructures,

(c) control of evaporation losses from reservoirs including from household storages,

(d) adoption of reduced agricultural water demand referring to cropping patterns, cultivation practices, and irrigation techniques, including the use of wastewater and saline waters,

(e) water recycling in industry and in energy generation

(f) reducing the water demand for recreational and urban uses, and irrigation of gardens and golf courses, including the use of low quality water,

(g) adopting tools and practices for lesser water use in house-holds and lawns,

(h) enforcing water price policies in relation to the used water volumes, specific uses, and the productivity of water used,

(i) adopting incentives for reducing water demand and consumption, and penalties for excessive water uses as well as for low quality effluents and return flows, and

(j) developing education programs and specific campaigns for adoption of water saving tools and practices by end-users and the population in general.

8.1.3. Water conservation and water saving to cope with drought

When water scarcity is due to drought, water conservation and saving requires policies and practices that are common with aridity as referred in Table 8.1. However, to cope with droughts requires a distinction between preparedness and reactive or mitigation measures, the first consisting in preparing for the application of the mitigation measures during drought.

Water conservation measures for drought preparedness include:

(a) development and effective implementation of drought watch systems as a main component of the meteorological and hydrological information systems,

(b) storage and regulation reservoirs to mitigate the effects of the diminishing availability of the resource during drought,

(c) controlling and planning for larger groundwater withdrawals aiming at augmenting the water availability during drought periods,

(d) improved conditions for operation, maintenance, and management of water supply systems, mainly for controlling operational losses, and providing for flexibility in operation, and high service performances,

(e) establishment of water allocation policies to be enforced under drought, which take into consideration the social, economic and environmental uses of the limited water resource,

(f) planning for the augmentation of available water resources during drought, including waste-water re-use and the use of non conventional water resources; however, note that water must be in accessible storage before the drought begins because it is unlikely any water will become available for capture until the drought ends,

(g) development of water technologies and practices to be adopted by the end users that help in reducing the demand and controlling the water wastes under conditions of diminished water availability,

(h) development of institutional conditions for drought preparedness and management, including for timely application of drought mitigation measures,

(i) establishing water pricing and financial incentives and penalties aiming at reducing water consumption and use and avoiding water wastage and misuse, including the control of water quality degradation by effluents and return flows,

(j) encourage households to save funds in good times, to buy water from delivery tankers during drought; institutions need to have a backup reservoir and extraction equipment to

provide water for carting to villages and households where local supply is totally exhausted,

(k) augmenting the public awareness on the economic, social and environmental value of the water, particularly oriented to produce a favourable attitude in regard to the adoption of drought mitigation measures.

When a drought occurs, *water conservation for drought mitigation* should be implemented. Then, measures and practices include:

(a) exploring the drought watch system to monitor the drought onset, development and termination, as well as to produce information for decision makers and water users,

(b) implementing changes in reservoir and ground-water management rules,

(c) enforcing drought oriented water allocation and delivery policies, and

(d) adoption of farm water storage and soil water conservation practices, which cannot help during drought but must be in place before the drought starts.

Water conservation is particularly important in the preparedness for droughts but it must be complemented with water-saving programmes, which are essentially reactive. *Water saving for drought mitigation* concerns measures and practices common to those for coping with aridity (Table 8.2), such as items (a), (b), (c), and (e) enumerated under 8.1.2 above, and others that might be specific for drought conditions such as:

(a) adoption of drought tolerant crops and drought oriented cropping patterns,

(b) reduction of the irrigated areas and/or adoption of deficit irrigation practices,

(c) extended use of inferior quality water for irrigation,

(d) adoption of water saving tools and practices for reducing domestic, urban, and recreational water uses, including the use of inferior quality water for irrigation of golf courses and gardens,

(e) ceasing supply by pipe and implementing tanker delivery. This is a drastic move but in a desperate situation it greatly reduces water consumption

(f) enforcing specific water price policies in relation to the used water volumes, the type of use~~s~~, and the efficiency of use,

(g) adopting incentives for reducing water demand and consumption and penalties for excessive water uses, for non authorised uses, as well as for degrading the available waters with low quality effluents and return flows, and

(h) developing campaigns for end-users to adopt drought oriented water saving tools and practices.

8.1.4. Water conservation and water saving to cope with desertification and water shortage

Desertification and water shortage are man induced and refer to problems such as land degradation by soil erosion and salinisation, over exploitation of soil and water resources, and water quality degradation. Therefore, they require that water conservation and water saving policies and measures combine with others oriented to solve the existing problems (Table 8.1). *Water conservation to combat desertification and water shortage* should often include:

(a) land and water use planning and management for re-establishing the environmental balance of the natural and man-made ecosystems, as well as in the use of natural

resources,

(b) appropriate reservoir and groundwater management rules, including artificial recharge and water quality preservation measures,

(c) water allocation policies that favour social and efficient use of water, including criteria relative to water quality,

(d) measures and practices for water quality management and focusing the control of related impacts on the environment, including monitoring,

(e) soil and water conservation practices in rainfed and irrigated agriculture, namely for erosion control,

(f) soil and crop management practices for restoring the soil quality, including soil moisture conservation,

(g) combating soil and water salinisation,

(h) strengthening the institutional framework for the implementation and enforcement of required policies and measures,

(i) education campaigns aimed at managers, farmers, factory managers and households, on how to save water and

(j) developing the public awareness for combating desertification and water shortage.

Water saving policies and practices also play a fundamental role in combating water scarcity due to desertification and water shortage. As for droughts, several measures and practices are generally common with those for coping with aridity (Table 8.2). Others should be oriented to combat desertification and water shortage and include:

(a) changes in crops and crop patterns for reducing the irrigation demand and taking advantage of soil moisture conservation,

(b) cropping and irrigation practices oriented to control non-point source pollution by agro-chemicals, fertilisers and erosion sediments,

(c) adoption of irrigation and drainage practices favouring salinity management and reduced water demand,

(d) water recycling for both industry and energy generation, and control of effluent quality to avoid pollution of surface- and ground-water,

(e) enforcing specific water price policies in relation to water use performances and the quality of effluents to favour adoption of practices that contribute for restoring the environmental balances,

(f) enforcing a policy of incentives and penalties in relation to users adoption of tools and practices that contribute to restoration of the water and soil quality and resource conservation,

(g) developing campaigns to encourage end-users to adopt water saving and environmentally friendly tools and practices.

Coping with water scarcity requires that measures, practices and policies of water conservation and water savings be effectively applied in relation to the respective causes, as discussed above. Those measures, practices and policies are analysed in the next sections in relation to the respective economic and social water user sectors.

8.2. Water use, consumptive use, water losses, and performances

8.2.1. Water use, consumption, losses, and efficiency

The terms efficiency and, more recently, water use efficiency are often used to express the performance of water supply systems and water use activities. However, there are no widely accepted definitions, and those terms may be used with different meanings. In an UNESCO conference dedicated to this subject, Garduño (1994) reviews a large variety of concepts for water use efficiency but does not propose any common definition. Tate (1994), when analysing the respective principles, assumes that water use efficiency "includes any measures that reduce the amount of water used per unit of any given activity, consistent with the maintenance or enhancement of water quality". This concept would assume both water conservation and water saving is synonymous with water use efficiency. For a better understanding of terminology utilised in relation to water use performances, a more consistent conceptual approach is required.

The term efficiency is often used in the case of irrigation systems and it is commonly applied to each irrigation sub-system: storage, conveyance, distribution off- and on-farm, and on-farm application sub-systems. It can be defined by the ratio between the water depth delivered by the sub-system under consideration and the water depth supplied to that sub-system, usually being expressed in percentage (Wolters, 1992). In case of on-farm application efficiency, the water depth delivered is replaced by the amount of water added to the root zone storage (Pereira, 1999). When referring to the system efficiency, it corresponds to the product of the efficiencies of the respective sub-systems. Adopting an output/input non-dimensional ratio, the term efficiency could be applied to evaluate the performance of any irrigation and non-irrigation water system.

As mentioned by several authors (e.g. Allen *et al.*, 1997, and Jensen, 1996), the term efficiency often leads to misconceptions and misunderstandings, mainly when increasing irrigation efficiencies is almost synonymous with creating more available water. In fact, there is the need to quantify the proportion of water used, i.e. diverted for a given use, that is consumed and the proportion that is not consumptive use and is available for reuse or becomes degraded after use. For the latter case, improving efficiencies would represent a reduction in water losses and contribute to the conservation of the available resource.

Another term commonly used, mainly in irrigation, is water use efficiency (WUE), but again no common definition has been adopted. Some authors refer to it as a non-dimensional output/input ratio. Others adopt it to express the productivity of the water, as a yield to water used ratio. In crop production, the term WUE is applied with precise meanings, such the yield WUE, which is the ratio of the harvested biomass to the water consumed to achieve that yield (Steduto, 1996). To avoid misunderstandings, the term "water use efficiency" should be only used to measure the performance of plants and crops, irrigated or non-irrigated, and the term "water productivity" (WP) should be adopted to express the quantity of product or service produced by a given amount of water used. Examples for WP are: kg of grain per m^3 of water in case of irrigation; metres of fabric per m^3 of water in the textile industry; kWh produced per m^3 of water in energy generation; m^2 of lawns irrigated per m^3 of water in recreational areas; or m^2 of area washed per m^3 of water in commercial areas. When the economic productivity of the water is considered, the numerator in that ratio would be replaced by the value of the product or service due to the water use.

In urban supply systems consumption data are usually available in terms of litres/person/day, and there needs to be an aim to have these numbers continually falling. In all the above cases, for farms, factories and domestic supply operations there need to be policies and incentives aimed at bringing water consumption to the lowest possible level for each unit of production or activity in all areas, i.e. increasing the water productivity in all uses.

8.2.2. Water systems and water use performances

New concepts to clearly distinguish between consumptive and non-consumptive uses, beneficial and non-beneficial uses, and reusable and non-reusable fractions of the non-consumed water diverted into an irrigation system or subsystem were proposed by Allen *et al.* (1997) and Burt *et al*. (1997). These consist of alternative performance indicators that are much more relevant than "irrigation efficiency" when adopted in regional water management for the formulation of water conservation and water savings policies and measures. These concepts and indicators are easy to adapt and extend to non-irrigation water uses.

These indicators can be adapted and extended to any water use or system to identify the respective performances under the perspective of water resources conservation as described in Table 8.3. These are more useful for water resources planning and management under scarcity and should lead to less misinterpretation than the term "efficiency".

Essentially, three water use fractions are considered:

- the consumed fraction, consisting of the fraction of diverted water which is evaporated or incorporated in the product, or consumed in drinking and food, which is no longer available after the end use,
- the reusable fraction, consisting of the fraction of diverted water which is not consumed when used for a given production process or service but which returns with appropriate quality to non degraded surface waters or ground-water and, therefore, can be used again, and
- the non-reusable fraction, consisting of the fraction of diverted water which is not consumed when used for a given production process or service but which returns with poor quality or returns to degraded surface waters or saline ground-water and, therefore, cannot be used again.

Each of the above fractions is then divided into two parts, corresponding respectively to the beneficial and the non-beneficial uses. Therefore, it is then easier to identify how water use could be improved, and how water savings should be oriented.

Adopting the indicators explained in Table 8.3, it can be concluded that water losses are those corresponding to non-consumptive and non-reusable quantities of water used, which define the non-reusable fraction. However, in the case of saline environments, part of the water loss is beneficial to the crop and the soil because it is used for leaching of salts and, therefore this loss cannot be avoided. The non-consumptive but reusable quantities of water are in reality not lost because other users or the same system downstream can use them again, mainly when reuse facilities are available. This reusable fraction, like the non-reusable, may be due to poor or less than optimal management, but may be required by the production or service process under consideration. It is often considered as lost but in fact it is only a temporary loss to the system and cannot be considered a loss from a hydrological perspective or under the overall water resource economy. However, the size of the reusable fraction

influences the cost of the system or sub-system operation and management and, moreover, it represents a non-necessary part of the demand, thus inducing negative impacts on the water allocation process and on the conservation of the resource.

TABLE 8.3. Irrigation water consumption, use and losses (adapted from Allen *et al.*, 1997 and Burt *et al.*, 1997)

	Consumptive	**Non-Consumptive and Non-Reusable**	**Non-Consumptive but Reusable**
Beneficial uses	*Irrigation*: ▪ ET from irrigated crops ▪ evaporation for climate control ▪ water incorporated in product	*Irrigation*: ▪ leaching added to saline water	*Irrigation*: ▪ leaching water added to reusable water
	Non-irrigation uses: ▪ human and animal drinking water ▪ water in food and drinking ▪ water incorporated in industrial products ▪ evaporation for temperature control ▪ ET from vegetation in recreational and leisure areas ▪ evaporation from swimming pools and artificial recreational lakes	*Non-irrigation uses*: ▪ degraded effluents from households and urban uses ▪ degraded effluents from industry ▪ degraded effluents from washing ▪ every non degraded effluent added to saline and low quality water	*Non-irrigation uses*: ▪ treated effluents from households and urban uses ▪ treated effluents from industry ▪ return flows from power generators ▪ return flows from temperature control ▪ non-degraded effluents from washing
Non-beneficial uses	*Irrigation*: ▪ excess soil water and phreatophyte ET ▪ sprinkler evaporation ▪ canal and reservoir evaporation	*Irrigation*: ▪ deep percolation added to saline groundwater ▪ drainage water added to saline water bodies	*Irrigation*: ▪ deep percolation added to good quality aquifers ▪ Reusable runoff ▪ Reusable canal spills
	Non-irrigation uses: ▪ ET from non beneficial vegetation ▪ evaporation from water wastes ▪ evaporation from reservoirs	*Non-irrigation uses*: ▪ deep percolation from recreational and urban areas added to saline aquifers ▪ leakage from urban, industrial and domestic systems added to low quality waters	*Non-irrigation uses*: ▪ deep percolation from recreational and urban areas added to good quality aquifers ▪ leakage from urban, industrial and domestic systems added to good quality waters
	Consumed fraction	**Non-reusable fraction**	**Reusable fraction**

Considering the irrigation sector, which has the highest share in consumption and demand in many water scarcity areas, it can be concluded that, assuming the concepts above, the improvement of irrigation efficiencies is of great importance under water scarcity. This is because higher efficiencies correspond to an increase of the beneficial use of the water for agricultural production. However, this objective has to be complemented by others such as:

- controlling the non-beneficial consumptive uses, particularly those associated to soil

evaporation, and evapotranspiration by phreatophyte plants and weeds receiving seepage and excess irrigation water,

- minimising the non-reusable fraction of the diverted water, thus avoiding percolation to saline water tables or the disposal of drainage water into saline water bodies which would degrade the water quality and would make it non reusable, and
- reducing the non-beneficial but reusable fraction by controlling deep percolation, seepage from canals, runoff return flows and canal excess water spills. These negatively impact operation and management costs and may be the cause for water-logging, competition by weeds, loss of nutrients and agro-chemicals, contamination of water bodies used for human consumption, and yield and income losses.

Box 8.1. presents, in summary form, the main performance terms adopted.

BOX 8.1. Performance indicators for water use and water systems

- *the consumed fraction of water use (WCF)*, consisting of the fraction of diverted water that is evaporated or incorporated in the product, or consumed in drinking and food, and is no longer available after the end use,
- *the reusable fraction of water use (WRF)*, consisting of the fraction of diverted water that is not consumed when used for a given production process or service but which returns with appropriate quality to non degraded surface waters or ground-water and, therefore, can be used again,
- *the non-reusable fraction of water use (WNRF)*, consisting of the fraction of diverted water that is not consumed when used for a given production process or service but which returns with poor quality or to degraded surface waters or saline ground-water and, therefore, can not be used again.
- *The water system or sub-system efficiency (SEf)*, consisting in the output to input ratio (%) relative to the system or sub-system under analysis.
- *The water productivity (WP)*, which could be defined by the ratio of the quantity of product or service produced to the amount of water used, i.e. diverted for that purpose.

8.3. Water conservation and water saving in urban areas

8.3.1. General aspects

The main supply problems faced in urban centres include the over-exploitation and depletion of the water supply sources, their contamination, high costs of operation and maintenance of supply systems, increased competition with other water uses (agriculture. industry, recreation), the observation of water quality standards, and the avoidance of water wastes. Cities often face a high incidence of leaks, the use of water-wasteful technologies, very low levels of water reuse, less appropriate water pricing and billing systems, water revenues that often do not cover costs, and a lack of public awareness of water scarcity. Unfortunately, these problems are more acute in water scarcity regions and less developed countries than in temperate climates and developed countries.

Urban water supplies are used in households, industry, and commercial areas, as well as for urban services such as city washing, combating fire, maintenance of recreational lakes and swimming pools and irrigation of recreational areas. Water conservation and water savings are required in all these domains, both in the hands of the users and directly by the municipal

authorities.

Municipal water services may be public or private. Despite differences in institutional arrangements, funding sources, water pricing and billing systems, and in relationships between water management authorities and their customers, water conservation and water savings may be approached using a common perspective.

Water conservation and water savings in an urban water system includes water metering, leak detection and repair, water pricing and billing, service performance, use of water in municipal and public areas and services, and development of public awareness on water saving. These items are developed below and the respective main issues, benefits and limitations are summarised in Table 8.4.

8.3.2. Monitoring and metering the water supply and distribution system

Metering is required at both the supply and distribution systems and at household connections. At the supply level, it concerns monitoring and measuring the water stored, being conveyed, and circulating in the distribution system. The resulting data produces information on the state of the system, and the respective variables. This information is vital for planning system developments and modernisation, for operation, maintenance and management of the systems in real time, and, in particular for planning and implementation of water conservation and water saving programmes. Metering at the household outlets is required for knowing the users consumption, for billing the customers in accordance with the respective water use, and for the support of measures to be enforced when water availability does not allow the supply to match the current demand.

Metering and monitoring the supply system has many advantages (Arreguín, 1994), mainly:

- Provides for an updated knowledge on the actual volumes stored and the discharges flowing in the water conveyance systems and in the distribution sectors, as well as water pressure and water levels at key nodes of the networks.
- Information on the supply and distribution network's state variables allows establishing the real time balance between water availability and demand.
- Generates information to assess the water supply balance in problem areas, namely where large differences in pressure may occur, and to evaluate the pressure distribution and uniformity along the distribution network, thus providing for improved management of the system.
- Produces data to evaluate the actual hydraulic conditions of the system's operation, including the detection of anomalies and malfunctioning of the networks, pumping stations, and regulation and control equipment.
- Produces information for planning and implementation of both preventive and corrective maintenance programs for supply lines, distribution networks, electromechanical equipment, water treatment plants, and storage facilities.
- Allows accurate planning of system extensions, developments, and modernisation.
- Allows estimating the volumes of water not being billed, to better identify the factors causing system losses, and to provide a basis for revision or upgrading of the rating policies.

TABLE 8.4. Water conservation and water saving in urban areas

Issue	Benefits	Limitations	Effectiveness
System monitoring and metering	▪ Information on the system state variables ▪ Estimation of system water losses, locations and causes ▪ Base for planning water conservation measures ▪ Support for implementation of water savings	▪ High investment and operational costs, mainly when an information system is created ▪ Needs an information system to be fully effective	High to very high
Metering	▪ Provides for fair billing ▪ Allows for water conservation planning ▪ Induces adoption of water savings by customers	▪ Needs investment costs ▪ May require system modernisation in case of old systems	High to very high
Water pricing and billing	▪ Induces water savings when prices increase with used volumes ▪ Helps people to appreciate the water supply, including giving water a social value	▪ Requires well designed price structure to be socially acceptable	High
Leak detection and repair	▪ Reduced volume of non beneficial water use ▪ Induces positive water conservation behaviour of customers ▪ More water is available to satisfy the demand	▪ Requires appropriate technologies	High
Maintenance	▪ Prevents equipment and conduit failures ▪ Minimises system water losses ▪ Supports good service	▪ Requires planning ▪ Requires system monitoring ▪ Requires appropriate technical staff	High
Regulation and control devices	▪ Improves the hydraulic performance of the network ▪ Helps prevent system failures ▪ Prevents contamination	▪ Requires appropriate technical staff ▪ High investment costs	High
High service performance	▪ Makes the customer responsive to water conservation policies ▪ Gives confidence to the customer to adopt water saving practices	▪ Custom oriented service requires high quality operation and management ▪ Higher costs	Moderate to high
Separated distribution of high quality and reused water	▪ Conserves good quality water to uses requiring such quality ▪ Implies wastewater treatment ▪ Effective water reuse for non human and outdoor recreational uses	▪ Very high investment costs ▪ Higher operation costs than for a single line distributor ▪ Requires the involvement of the users	High to very high
Legislation and regulations	▪ Create a framework for adopting water conservation and saving ▪ Enforce restriction policies when drought increases scarcity ▪ Favours connections with public water authorities	▪ Needs an appropriate institutional system for enforcement	High when duly enforced
Economic incentives and penalties	▪ Favour the adoption of water saving devices and practices ▪ discourage water wastage	▪ Requires appropriate institutional framework ▪ Needs careful planning	High to very high
Public education and information	▪ Create public awareness of water conservation ▪ Promote the adoption of water saving practices and devices by customers and the population	▪ Require well planned and co-ordinated efforts of public authorities, schools, water companies and municipalities	High

- Produces data to evaluate operation, maintenance and management programmes and to support a system of information and control.
- Supports planning of water conservation measures, and establishment of drought preparedness plans and real-time drought mitigation operational and managerial plans.

Despite advantages, there is a limited use of the metering data when appropriate databases are not installed and used. To fully explore the benefits of metering and monitoring urban water supply systems, it is advisable to make meter data collection, handling and analysis part of an information system, which should also include the production of control, operation, maintenance and management reports. Automation of meters enables the data collected to be transmitted in real time to the information centre, thus to be processed and analysed also in real time.

8.3.3. Metering at customers outlets

Metering the water delivered to customers is essential for billing, to reduce water use and, when a water savings price policy is enforced, to induce customer water savings. Arreguín (1994) reports that billing for the volumes of water used induces by itself a reduction in use of up to 25% in areas that previously had no metering. However, as shown in a study by the Mexican Institute of Water Technology referred by Arreguín (1994), the upper and lower socio-economic classes were generally not responsive to metering, while the middle classes reduced water use by up to 50%.

Metering customer water use has the following main advantages:

- Customers pay for the used volumes, which is far better than to be billed by any other criterion
- Customers, mainly those of the middle class, tend to reduce water use when they realise that excess water use has a cost
- Water savings by the customers provide for improved use of the resources available, thus for better service.
- It is relatively easy to fix the water price to cover the full costs of operation, maintenance and management, and thus to improve both the network and the water service, and to provide for avoidance of health hazards
- Information on metered volumes provides an accurate knowledge of consumer use patterns, which are important for planning system developments and modernisation, as well as water conservation and water saving programmes, particularly under drought conditions.

Implementing a metering system requires appropriate planning, from the installation stage through the maintenance phase. Meters with the appropriate capacity should be used. The use of undersized meters leads to false readings and a shorter service life as a result of excessive wear on its components. Conversely, using an oversized meter implies a higher initial investment and less accurate readings of low flow rates.

Although the ideal is to meter 100 % of all residential outlets, this is not always possible owing to the installation costs of a metering system. Studies carried out in various Mexican cities by the Mexican Institute for Water Technology, as reported by Arreguín (1994), have shown that 10 % of the meters installed account for 51% of the total volume used, taking only

major consumers into account. The next 10 % meters account for about 14% of the volume measured, while the last 10 % concern only 3% of the total volume. It is estimated that if 30% of the residential customers are metered, as much as 75% of the volume can be measured.

Strategies for the installation of meters when capital investment does not allow for metering all the customers can thus be defined as follows (Arreguín, 1994):

- Selective metering. Once the major consumers are identified they should be metered first, then continuing the metering process until the target level for the locality is reached.
- Metering by sectors. This option involves metering groups of users having similar consumption patterns and dividing the cost of the water used among them.
- Combined metering. This is a combination of the two systems above, which is applicable when water use is differentiated. A sector meter can be installed at the upstream end of each sector and individual meters are installed for major consumers. The water use of the non-metered users can be estimated by difference.

8.3.4. Maintenance of urban water supply systems

Maintenance may be preventive and reactive. It plays a major role in water conservation. The main purpose of preventive maintenance is to ensure the proper functioning of the water supply system, from the upstream water sources to the customers. Consequently, it includes the network reservoirs and conduits and respective equipment, the pumping stations, the water treatment plants, and the metering system. For the latter, meter readings need to fall within a well-defined range of accuracy. A study in Mexico reported by Arreguín (1994) has shown that 23.4% of the meters over-recorded water use, 71.4% under-metered and only 5.2% measured accurately.

Each utility and sector should have its own program of maintenance. Computer programs may be helpful in establishing and controlling maintenance programmes. Reactive maintenance needs to occur as required. Reactive maintenance takes place in response to information provided by the field personnel, meter readers and users about system failures, equipment disrepair, and inaccurate meter readings.

8.3.5. Leak detection and repair

System losses in urban drinking water supply systems are mainly due to evaporation and seepage in storage and regulation reservoirs, and leaks in water treatment plants, in distribution networks and in home outlets. The used volumes not metered due to inaccurate or non-existent metering, the unauthorised outlets and the unrecorded volumes used by municipal services, such as for watering public gardens or used from fire hydrants, are often accounted as losses, despite the fact that they constitute beneficial uses. Also often accounted as losses are the leaks in households. Summarised in Table 8.5 are the results of another Mexican study covering 15 large cities. It shows that leaks in the system and through the outlets are very high, far larger than leaks in households. However, reported leaks in the network are low, much below what is detected by careful monitoring, particularly in old systems. Leaks in the network are generally higher in systems that breakdown very often.

TABLE 8.5. Results of the evaluation of the water losses in 15 large cities in Mexico (Arreguín, 1994)

	Taps with leaks	Volume lost through outlet leaks	Volume lost at network level	Volume not accounted due to under measuring	Total losses in system
Average (%)	15	26	10	2	38
Range (%)	5-38	14-59	1-26	0-14	24-60

Leaks in the supply network may be visible or not. Water rising through the soil or pavement provides a visual indication, but it is common to have invisible leaks where the water flows into the drainage system or to an aquifer.

The causes of leaks vary, depending on the geotechnical soil characteristics, quality of construction, materials used, particularly in joints and at valve locations, flow pressure and pressure variation, age of the network, water chemistry, and operation and maintenance practices. Leaks can result from crosswise or lengthways cracking of the conduits, being caused by surface vibrations, poor construction, fatigue and manufacturing flaws of the material, or sudden pressure variations due to fast manoeuvring of valves. Other causes include rusting, poor pipe joints or valve failure.

In home outlets, faults can be due to fissures, perforations, and cuts or loose fittings. These are due to poor quality materials, poor construction; and external loads.

Leak detection and repair is beneficial to reduce:

- system water losses, i.e. the non beneficial water use fraction,
- energy consumption, wear of equipment, and operational costs,
- contamination risks of the network,
- negative impacts of the percolating water.

Leak detection and repair is also beneficial to better utilise the available resource and to facilitate the promotion of citizen awareness in water conservation. That activity may be performed easier with help of models, which support the analysis of a drinking water system (Arreguín, 1994). Descriptive analysis models provide an initial understanding of the system, including the analysis of records of operations, failures, and repairs undertaken, so making it possible to estimate the percentage of losses in the network and in home outlets in the different sectors of the system. Predictive models are based on the knowledge of the age of the network, the materials used, rate of corrosion, most frequent kinds of failures and respective repair to predict the behaviour of the network and its losses. Physical analysis includes fieldwork to detect leaks in the distribution network, home outlets and any other part of the system.

Several leak detection methods exist including: (a) the acoustic method, based on the fact that leaks under pressure produce sounds that can be detected by using appropriate sensors, amplifiers and headphones; (b) the so-called Swiss method consisting of injecting water under pressure into a reach or a sector of the network and measuring the amount of water required to keep the pressure constant, where the resulting volume equals the amount of water leaked; (c) the correlation analyser method which is based on recording the noise produced by a leak using sensors placed up- and downstream of it and then processing the two signals by a correlation analyser to give the respective distances to the leak location; and (d) the tracing method, where tracers are injected upstream and then the leak site is detected with

support of chemical or radioactive tools (Garduño and Arreguín, 1994).

8.3.6. Water pricing

Historically, in most countries, water costs have largely been or still are subsidised. In others, water is supplied free. It is of importance to establish rate policies that emphasise greater user involvement in water conservation and saving. When users are charged appropriately for water services, the water use as well as the water waste tends to decrease.

Water pricing can help to save water if the price structure meets some essential conditions:

- prices must reflect the actual costs of supply and delivery to the customers to ensure the sustainability of the water supply services and the maintenance of conduits and equipment;
- the price rate should increase when the water use also increases to induce customers to adopt water saving and conservation;
- different price rates should be practiced for diverse types of water use in municipal supply, e.g. differentiating domestic indoor uses from gardening water uses; when water is more scarce than usual, prices for less essential uses could be modified earlier;
- differential increases in price must be large enough to encourage water savings;
- prices must reflect the quality of service, i.e. poor and non reliable service cannot be provided at high cost but costs must change as soon as service is improved.; and
- any change in pricing must be accompanied by information and education programs that support an increased awareness of the customers of the value of water and water supply services.

Water benefits are different for each type of user. In urban areas there are several types of water use: domestic, public, industrial, commercial, services, construction, and recreational. Each of these categories reacts differently to the same financial spur in charging for the service, so it is important for the rate structure to be properly designed (Arreguín, 1994). This involves knowledge on trends in costs and the respective price structure, on trends in the water market including its seasonal variations, and information on users' categories and their ability to pay. Other variables that affect decisions are the policies on subsidies and on fines and penalties for water misuse and abuse.

Users must be billed correctly and informed of the amount of their consumption. Increases and adjustments in prices must be clearly linked with the costs of water services. If they are not prices may become subject to external influences (e.g. the need to raise tax income) and fail to be accepted by the customers. In such a case the customers may react negatively to water saving programmes. Therefore, the political authorities and the users must be clearly informed of why changes are needed, through information campaigns that target the different categories and social sectors, explaining the facts simply and honestly.

8.3.7. Regulation and control equipment

Important progress in design and equipment for urban water supply systems has been made during the last decades. However, investment costs still are high limiting the adoption of respective developments, mainly in less developed areas, where funds are limited but population growth is very high. Particular attention must be paid to the adoption of

appropriate regulation and control devices in the network because this equipment plays a fundamental role for the quality of service, and therefore in the implementation of water conservation and water saving programmes. This equipment mainly relates to:

- support appropriate hydraulic functioning of the network, including the avoidance of sudden variations in pressure due to the manoeuvre of gates and pumping stations in relation to variations in demand, which could damage conduits and equipment,
- prevent system failures,
- prevent the contamination of the network,
- provide for flexibility in operation,
- maintain adequate service pressure, mainly when the network covers areas with less favourable topography, with large variations in elevation.

The adoption of advanced regulation and control equipment is difficult for small networks and for more remote areas because it requires appropriate technical staff, and investment and operation costs are high.

8.3.8. High service performance

A water supply company may have good water metering, pricing and billing systems but fail in inducing water saving from the customers when the service provided is poor. The quality of service may be evaluated using indicators such as reliability and equity.

A water service is reliable when there is a very high probability that the discharge and pressure delivered to a customer corresponds to those contracted between the water company and the customer. The service is not reliable when there are frequent breaks in the delivery, or when only a small discharge and reduced pressure are currently available to the customer. When the service is not reliable, the user tends to consider that the water price is always excessive and not enough water is made available to him and there is no need to save water. When frequent breaks occur, the user may be forced to create his own reserves of water, which he may waste as soon as he receives a better supply.

Problems may be aggravated when there is no equity in the service. Equity occurs when all customers receive a similar service in terms of discharge and pressure disregarding the location of the user, the volume of water used, the social class and the type of water use (e.g. domestic, commerce, services). When equity does not exist and this is recognised by the poorly served customers, these react negatively to the water price and generally are unwilling to adhere to a water saving program.

As discussed earlier, when a monitoring and metering program exists, information becomes available that allows recognition of the quality of service in terms of reliability, and the existence of locations or type of users that are critical concerning equity of service. When problems that affect them are solved, then the users behaviour may become more favourably oriented towards saving water, which in turn may have positive impacts on the water service.

8.3.9. Dual distribution networks for high quality and for treated reusable water

Diverse water uses in urban areas require different water quality. High quality water is definitely required for uses such as drinking, food preparation, or bathing. However the largest fraction of this water is not consumed but returned as effluent with degraded quality

and is not reusable for the same purposes. On the other hand, uses such as toilet flushing, heating, floor washing, or irrigation of lawns and gardens do not need such high quality water and could use treated wastewater.

Originating from these different requirements, in urban areas where extreme water scarcity exists, a feasible but expensive solution is to duplicate the distribution network, mainly in the neighbourhoods or sectors where water users can manage with inferior quality water for uses other than human consumption (Okun, 2000). At the limit, different sewage systems may be built, separating the less contaminated and less charged effluents from the more degraded ones. The two effluents may require different treatments and may attain different quality levels, and therefore may have different uses. Urban drainage rainwater may also be treated and added to the higher quality treated urban effluents.

This solution has several advantages under the water conservation perspective:

- urban, namely domestic effluents are treated and thus added to the available resource,
- the scarce high quality water is used only for more exigent uses,
- uses demanding inferior quality water may more easily be satisfied through treated wastewater and urban drainage rainwater.

Despite the usefulness of this approach, this is difficult to implement because it requires very large public investments, as well as important investments by the customers in their homes or buildings, and it is necessary to create the public awareness required for a wide acceptability of such a new solution. Financial incentives such as subsidies for investment and deductibility on the taxes may then be required.

8.3.10. Legislation and regulations

Water laws give each country its general framework for water use and conservation, and are complemented by regulations, which establish the practical application of the legal water policies.

Regulations to improve water savings are often of a restrictive nature. In most cases, they are established for long-term application, but they may be applicable only during periods of limited water availability such as droughts. In that case they generally require very strict surveillance and should only be applied when they are really necessary.

Long term regulations concern questions such as the characteristics and standards for indoor plumbing fixtures, or maximum volumes per flush in toilets (e.g. 6 l/flush), or maximum discharge in showers (e.g. 10 l/min.). Regulations also include requirements to replace old type toilets, compulsory use of equipment for filtering, treating and recycling the water in swimming pools, etc. Temporary regulations may concern the prohibition of use of hoses to wash motor vehicles or sidewalks.

8.3.11. Incentives and penalties

Incentives and penalties of a financial nature are required as a complement of the water saving campaigns, and as the prime measure to enforce regulations.

Incentives are often required for urban water supply companies, municipal or private, mainly in less developed areas, to implement high cost water conservation technologies, which may require an expensive investment. Examples could be the full coverage of every

customer with metering, the modernisation of the network in an area of low class population where reliability and equity are low, or the investments required to install separate supply and sewage systems.

Incentives to urban customers are required when the implementation of water savings implies investments in homes and buildings, in particular for low-income populations. Examples are the installation of modified supply and sewerage systems when separate supply and sewerage networks become available in the neighbourhood, the replacement of toilets for reduced flush volumes, or the adoption of pressure control devices. Incentives could then be given by the government, the municipality or the water supply company. Incentives by the government to the water company and the customers generally relate to

- credit facilities relative to a specific investment for water conservation and saving,
- lowering or exempting custom taxes for selected goods or equipment,
- subsidising a percentage of the investment costs, which could vary with the income level of the customers, and
- fiscal benefits for the water company or the customers in relation to selected investments.

Penalties essentially consist in discouraging water users from adopting practices and devices opposed to regulations. Penalties and fees are the best measures to enforce regulations. While incentives are given to those seeking them and proving the correspondent rights, penalties require control by water company personnel, municipal services or the police. Enforcing penalties and fees involves additional costs in personnel and in bureaucracy, including that relative to the Court when the citizen refuses to pay. Therefore, the implementation of a penalties and fees policy needs appropriate planning to ensure that it can be effectively applied and be useful to the community.

8.3.12. Information and education

Water saving programs need the users participation to be successful. Furthermore, information and education campaigns are required. The same requirements exist for successful implementation of legislation and regulations or to achieve water saving objectives in relation to the adoption of water metering and water pricing.

Information to the users may include leaflets sent out with bills, publicity campaigns in the press, radio and television, billboards on streets and public transport vehicles. Special campaigns for water saving may also include the free distribution of water-saving devices, assistance with the cost of investments required to renovate or upgrade household water systems, or allow tax deductions for specific water saving investments.

Education mainly concerns the introduction in primary and secondary school curricula of the essential aspects of the hydrological cycle and water sources (see Chapter 10). It should also cover limitations in water use, causes and other considerations related to water scarcity, the costs to mobilise and supply water, the main water uses and benefits, and, finally, how to properly use both water indoors and outdoors.

8.4. Water savings in domestic applications

Domestic water use can be classified under indoor and outdoor uses. In a typical household having outdoor facilities, nearly 50 % of the water use is for the garden (Stanger, 2000).

Water uses in commercial and services buildings are considered herein together with the domestic ones since they are similar, they are very often located in the same neighbourhood or distribution sector, and water saving measures are common. Also common are water uses for hotels and restaurants. A summary of water savings in domestic uses is given in Table 8.6.

8.4.1. Indoor water uses and savings

A few years ago, as much as 35% of indoors water use could be accounted for by toilets, 30% by showers, and 20% by clothes washing (Arreguín, 1994). Nowadays, there is a slight change: 33 % concern showers and bath, 24 % are relative to toilet flushing and 22 % to laundry water use (Stanger, 2000). The main attention must be given to the following types of water uses:

(a) *Toilets:* Traditional toilets use 16 to 20 litres per flush, which means an average of 80 to 100 litres per day per capita. Leaks from the toilet reservoir are the most common system losses in domestic water use, occurring in 15 % of cases as reported in Table 8.5. Water saving in toilets may be achieved by using several means such as:

1. toilets with a reduced reservoir, such as 6 litres per flush,
2. toilets with double discharge, one producing larger flushes, the other a smaller flush,
3. placing containers or bags filled with water in the tank of traditional large volume toilets to reduce its capacity; however, the toilet's siphoning effect may be reduced.
4. changing to longer discharge siphons in traditional toilets, which reduces water flushes,
5. toilets having flushes controlled by the pressure in the mains or a pressure regulation device, so that volumes of water discharged may be near 6 litres per flush.
6. special toilets such as with pressurised tanks having the feed line connected to a hermetically sealed tank, so that the pressure within the tank equals the difference in levels between the free surface of the main water tank and the surface of the toilet tank, or biological toilets or incinerators, which degrade faecal matter in deposits located below and turn it into fertiliser.
7. toilets where leaks are easy to detect and repair or toilets less susceptible to leaks such as pressurised tanks without the conventional fittings, and models that substitute siphons for new design fittings.

(b) *Showers and bathing* Showers take second place in domestic water demand. Water savings include:

1. using shower-head designs that limit the discharge to not exceed fixed values such as 10 l/min,
2. using flow or pressure limiting devices to reduce shower discharges to target values,
3. reducing the time for showering,
4. preferring shower to immersion bathing,
5. controlling leaks in shower fixtures, such as those caused by worn gaskets or loose nuts, which are simple to repair.

TABLE 8.6. Water savings in domestic water uses

Water uses	Techniques	Applicability
Indoors		
Toilets	▪ Use reduced flush ▪ Use leak proof fixtures	▪ Easy, affordable costs
Showers	▪ Use reduced discharges ▪ Shortening shower duration	▪ Easy but needs willingness
Basin taps	▪ Reduce pressure and discharge ▪ Use valves for automatic closing ▪ Keep closed when not directly in use ▪ Dish wash in a basin, not in flowing water	▪ Easy but needs care
Cloth washers	▪ Use when full ▪ Use washers with less water requirement	▪ Easy
Dish washers	▪ Use when full ▪ Use washers with less water requirement	▪ Easy
Outdoors		
Gardens and lawns	▪ Irrigate to refill the top 15 cm of soil ▪ Adopt information or tools to decide the irrigation frequency ▪ Select an irrigation method that helps to adopt reduced and localised watering, such as drippers and microsprayers ▪ Irrigate by night, out of the high demand hours and when evaporation is minimal ▪ Under restrictions reduce irrigation frequency, reduce volumes to annuals and lawns but keep irrigating trees and shrubs ▪ Use mulches to avoid soil evaporation ▪ Control weeds ▪ Avoid plants from humid climates ▪ Select native and xerophyte plants	▪ Costs are affordable ▪ Needs public awareness ▪ Requires information
Side-walks and car washing	▪ washing with a hose is water wasteful ▪ dry clean side-walks ▪ use recycling in car wash services	▪ Needs public awareness
Swimming pools	▪ use water purification tools ▪ cover for evaporation control	▪ Affordable costs
General issues		
Leak control	▪ apply good quality materials and construction techniques ▪ detect and repair	▪ Expensive but effective
Pressure control	▪ use pressure regulators to avoid excessive discharges	▪ When pressure is excessive

(c) *Basin taps:* several water saving measures may be applied in water use from taps in bath rooms and kitchens:

1. flow reduction by using aerators, which add air to the stream and disperse it, increasing the spread and the washing efficiency, reducing flow as much as 6 %,
2. flow reduction by using pressure control devices when the pressure is too high,
3. in hand washing basins, use of valves with sensors that activate the water flow only when the hands are placed beneath them, or use of valves for limited flow time in

hand washing basins, caring about keeping taps closed when not being required, such as keeping them closed while soaping the hands and opening again to wash, or wash teeth using a glass of water, not flowing water,

4. use of tap valves easy to close and re-open that make it easier to have water flowing only when it is necessary,
5. dish washing in a basin, not with flowing water,
6. controlling leaks in tap fixtures such as caused by worn gaskets or loose nuts.

(d) *Washing machines:* Water savings in these machines can be achieved by:

1. loading the washers with the appropriate weight of clothes, using the water levels necessary for efficient operation; some modern machines may require less water when half charged,
2. using washers that require less water; front loading washers can use up to half the amount of water (up to 50 % of the hot water and 33 % of the detergent) required by tub or top loading washers; modern washing machines have reduced water use, by up to 25 % in comparison with traditional models,
3. follow instructions of the manufacturer on selecting the programmes since they may have different water and energy demands.

(e) *Dish washers:* Water savings concern:

1. selection of the machines that require less volume of water to perform the same operations; some modern machines use about one third that of old models.
2. load the machines to full capacity; modern dishwashers have somewhat reduced demand when half charged,
3. follow instructions of the manufacturer on selecting the programmes since they may have different water and energy demands.

(f) *Control of indoor leaks:* Leaks in pipes, plumbing fixtures and toilets are very frequent and may be difficult to detect. One way to solve the problem is to use leak-proof fittings and other materials whose specifications correspond to pressures to be used as well as to the temperature of the water. Hot water pipes and plumbing often leak. After installation of the pipes, a test must be performed to check joints and valves before walls are closed. Safety valves must be installed for easy repair operations.

8.4.2. Water savings in outdoor applications

(a) *Lawns and gardens:* Water saving practices listed under subheading 8.5.(a) can be easily adopted for house gardens and lawns. These concern irrigation methods and scheduling, and irrigation practices when restrictions in water supply are enforced.
The conversion from turfgrass to xeriscape (low water-use landscape) in house gardens has been studied in Nevada, USA, where typically 60 to 90 % of potable water drawn by households is used for outdoor irrigation. A xeriscape is characterised by sound landscape planning and design, limited use of turf, use of water-efficient plants, efficient irrigation, soil amendments and mulches, and proper landscape maintenance procedures. The study, concerning 499 properties, shows that the adoption of xeriscape reduced the water use for outdoor irrigation by 33 % relative to a turf landscape, that proportion being 39 % during the summer months (Sovocool and Rosales, 2001). This may represent an enormous saving of good quality municipal water for areas of hot, dry extreme climates.

(b) *Sidewalks:* should be cleaned dry. To wash stone or concrete sidewalks with a flexible hose is water wasteful.

(c) *Swimming pools:*

1. water used to fill a swimming pool can be continuously recycled, clarified and purified by using easy to handle portable equipment and appropriate chemicals. It may be then renovated after one year or so,
2. leakage losses may be prevented using appropriate construction materials and techniques. When empty it is advisable to check the state of the sides and bottom and perform the appurtenant repair if necessary,
3. evaporation losses can be minimised by covering the pool when not in use.

(d) *Car washing:*

1. washing cars with a hose is water wasteful. It is recommended that just a bucket and cloth be used.
2. car wash services should recycle or reuse water.

Most of the fixtures discussed above, both indoors and outdoors increase their rate of discharge in direct proportion to the water pressure. In areas where pressure is high, the use of pressure-reduction valves is recommended.

8.5. Water conservation and savings in landscape and recreational uses

Landscape and recreational water uses include a variety of outdoor and indoor uses and can be managed by municipal, governmental or private institutions, but all have in common the fact they are for public use. Landscape irrigation represents more than 20 % of irrigation water use in the United States, from which about 10 % are for irrigation of gulf courses (Shank, 1996). Water conservation and water saving issues are summarised in Table 8.7.

(a) *Gardens and lawns:* Water savings in garden and lawn irrigation can be achieved through several practices:

1. Adopting appropriate garden watering practices, particularly avoiding excess water application. The amount of irrigation water that should be applied varies with the climate. Because most garden plants are shallow rooted, the recommended depth of soil moistening during the watering period is only 15 cm. Irrigation should stop when ponding or runoff occurs, which points out that water applied is in excess of infiltration.
2. Using irrigation equipment that helps reduce irrigation water use, preferably micro-irrigation: localised drip irrigation for trees, shrubs and flowers in a row; microsprayers for lawns and flowers in a wider space; bubblers or drippers for small basins. Drip lines may have drippers at different distances according to plant spacing, and may be laid or buried in a curvilinear orientation as the plants. Microsprayers may have a variety of spray heads to irrigate in circles, half circles and corners with different angles; they also have a variety of discharge, wetted diameters, wetted patterns and drop sizes, including mist, which can be adapted to every kind of garden plants.
3. Using simple information for scheduling irrigation: plant appearance, soil touch and feel, broadcast information on evapotranspiration, or instruments for indicating the

soil water depletion in the upper 15 cm soil layer. These instruments, although not very precise, are helpful to city customers, and are easily available in garden shops.

TABLE 8.7. Issues in water conservation and saving in recreational water uses

Water use	Issues	Applicability
Gardens and lawns	▪ Selection of ornamental plants less sensitive to water stress ▪ Adopt water reuse ▪ Adopt well designed and automated drip and micro-spray irrigation systems ▪ Establish irrigation management strategies to cope with increased levels of water scarcity ▪ Irrigate by night ▪ Use soil mulch and weed control	Requires technological support and training of personnel to be effective
Pools and ponds	▪ Use water purification tools when not used to support life, such as fish ▪ When having fish, use a technique similar to fish ponds, or flowing water for other uses, e.g. as irrigation tanks	Requires planning and technical support to personnel
Golf courses	▪ Adopt an irrigation design oriented for easy management under scarcity ▪ Reuse treated wastewater for irrigation ▪ Establish irrigation management strategies to cope with increased levels of water scarcity	Requires new approaches in design and management, and training of personnel
Parks and Lakes	▪ Enforce water quality policies ▪ Adopt integrated resource management	Needs involvement of public authorities
Sport areas	▪ Sprinkler irrigation of green areas with high uniformity ▪ Adopt precise irrigation	Requires technical support
Swimming-pools	▪ Use purification tools and chemicals ▪ Enforce health prevention measures	Easy
Indoor facilities	▪ Adopt controlled flush toilets ▪ Adopt limited flow showers ▪ Use time controlled hand-wash taps ▪ Use controlled discharge kitchen taps ▪ Care for leak detection and repair	For most of the issues, they follow common sense practices
General issues	▪ Publicise water saving measures ▪ Advertise to make water users aware ▪ Educate children and youth	Favours public behaviour

4. When strong restrictions on water supply are enforced for outdoor irrigation, the following strategies may be adopted, in the order of increasingly stringent restrictions:
   - to decrease the frequency of irrigation but apply the same amount of water at each irrigation; to decrease both the frequency and the irrigation volumes;
   - to abandon the irrigation of annual plants, so maintaining the irrigation of the perennials only;
   - to abandon the irrigation of lawns but watering trees and shrubs to keep them alive when they are difficult to replace.
5. Adopting automation when micro-irrigation or sprinkling is used. Automation makes it easier to adopt the water saving irrigation practices referred above, and allows for irrigating by night, when wind drift and evaporation losses are minimal, and water demand to the supply system is also lesser, so minimising impacts on the functioning

of the supply system. When automation is not available, the best time to irrigate is between 4 and 8 a.m. or, when this schedule may be inconvenient, an alternative is between 8 p.m. and midnight.

6. Using mulch for soil water conservation, particularly to control evaporation. Various types of mulch can be used in gardens: organic mulch made from wood residuals, stone mulch, namely of gravel type or riverbed stones, coarse sand, and straw mulch. Other products for mulch may be available in gardening shops, or be prepared in public gardens with available materials.
7. Adopting weed control is also important because weeds compete with garden plants for water and nutrients.
8. Selecting garden plants native to the region or well adapted to the prevailing environmental conditions, including low water demand, is a potential condition for successfully coping with water scarcity. On the contrary, choosing ornamental shrubs and trees from temperate and humid climates creates additional water requirements and great management difficulties since these plants are very sensitive to water stress. An alternative to native plants, or in combination with them, are the ornamental xerophytes, such as cactus, which are extremely efficient in water use. When ornamental shrubs and trees from temperate and humid climates are selected for gardens in water scarce areas, it is advisable to consider the use of water of inferior quality for irrigation, including treated wastewater. Microirrigation systems (drippers and bubblers but not microsprayers and microsprinklers) are the most adequate when reused wastewater is applied. Filtering should then be carefully designed.
9. Careful layout and pipe network design as well as appropriate selection of emitters and filters are required. A good design and good quality of materials avoid uneven pressure distribution, non-uniform discharges, and frequent system failures. It makes automation easy and favours the implementation of water saving strategies. Poor design and low quality equipment cause irrigation management to be difficult, and waste of water and plant stress to occur more easily.

(b) *Pools and ponds:* two situations can be considered:

1. When pools do not support life, i.e. no fish are present, the best water saving practice is to avoid the need for frequent replacement of the water. This can be achieved by applying a treatment technique for water clarification to combat water eutrophisation.
2. When pools and ponds support life, such clarification treatment is not viable because of chemicals affect the fish. If a prime objective is to have fish, then technologies similar to those for fish-ponds may be adapted. Life and clear water may be achieved if pools and ponds are used as irrigation tanks with permanent flowing water. However, it may be required to reduce the stored volumes in proportion to the volumes used in irrigation to avoid eutrophisation, i.e. to keep the water moving. To treat the water against eutrophisation may be expensive and not justified when heavy restrictions are applied. Ponds with standing water have to be avoided for environmental and heath protection since they constitute an attractive base location for water borne diseases.

(c) *Golf courses:* large volumes of water are required to fully irrigate golf courses. In general good design and equipment are used since this is a high-income generation activity. Water savings can be attained when:

1. Sprinkler or, less often, micro-sprinkler irrigation systems are utilised. Irrigation is better performed at night, so evaporation and wind drift losses are minimised. Different requirements in the various parts of the area may be satisfied when the system is designed accordingly. Therefore the system should be designed for different irrigation management in each of the grassed areas near the holes, in the area of approach, on the fairways and in the surrounding areas.
2. Grass may be selected, at least for certain areas in the green, among species that have less water requirements and are less sensitive to water stress.
3. Under-irrigation problems may be avoided when treated wastewater is used. Favourable conditions for its use exist because these irrigation systems are automated, night irrigation is the rule, and the direct contact of humans with the irrigation water is minimal. However, monitoring is advisable to prevent any negative health impacts. Filters are then required for safe operation of the irrigation system depending on the characteristics of the water (for wastewater reuse, see sub-heading 7.2).
4. When limited water is available, the following deficit irrigation strategies may be adopted as supply restrictions increase:
   - abandon irrigation outside of the fairway areas,
   - reduce irrigation in the fairway area keeping the greens fully irrigated ,
   - under-irrigate all areas except the green near the holes,
   - under-irrigate to just keep the grass alive. To play under these conditions is more difficult but is more challenging!

(c) *Parks and Lakes.* Water uses concern the maintenance of ponds, the irrigation of gardens and lawns, and the irrigation of plant nurseries and greenhouses. Issues relative to the first two have been described above. For the latter, approaches outlined below for irrigated agriculture may be adopted. Lakes are usually at low levels or dry when high water scarcity occurs and, often, recreational lakes are exploited for adding to the limited available resource. The main issues concern water quality preservation since the concentration of pollutants increase when flows supplying those lakes decrease. Therefore, the focus of attention should be on the enforcement of water quality policies in the upstream areas, aiming at limiting point-source pollution and at expanding the treatment of effluents to be returned to nature.

(d) *Sport areas and swimming pools.* They consist of indoor facilities, which are dealt under 8.5 (f), below, and outdoor support areas. In the latter, water consumption mainly concerns the irrigation of green areas, washing of stadium seats, floors and parking lots:

1. *Irrigation of green areas:* Sprinkler irrigation with portable pipe laterals or hand pull hose systems are practised. To keep fields in good conditions for sports practice, grass water stress is not allowed. To avoid health hazards, using treated wastewater is not viable. Then water saving practices concern:
   - adoption of an optimal irrigation schedule, which can easily be performed if information on evapotranspiration is made available, particularly through the mass media,
   - use of a well designed system having high uniformity of application, and adopting proper equipment and maintenance (e.g. Smith, 2001),
   - irrigating at the early hours of the day, when wind and evaporation are small, and pressure available from the supply system is higher and has reduced time variability.

2. *Washing*: Saving water in cleaning activities is mainly possible by replacing washing by cleaning dry, using cleaning machines in large areas, and avoiding hose washing, which is always wasteful of water.
3. *Swimming-pools:* water savings consist of:
   - using purification equipment and chemicals that avoid frequent refills of the pools,
   - adopting health preventive measures for users,
   - caring about leak detection and repair.

(e) *Indoor facilities:* water uses in indoor public facilities mainly concern the toilet area in public buildings and in support of outdoor activities, the shower area in sports facilities, food areas in support of recreational activities, and washing of floors and special rooms. Corresponding issues for water saving are common to those analysed for domestic uses, which are analysed under sub-heading 8.4.1. Essentially, they consist in:

1. *Toilets:* recommendations given under 8.4.1.(a) apply, particularly toilets with double flushing and toilets with flushing controlled by sensors.
2. *Showers:* controlled discharges as suggested under 8.4.1. (b).
3. *Basin taps in bath rooms:* among recommendations under 8.4.1 (c), those for adopting valves with sensors that activate the water flow only when the hands are placed beneath the taps, and valves for limited flow time are most appropriate.
4. *Basin taps in kitchens:* among items referred under 8.4.1. (c), recommendations mainly concern flow reduction devices, easy manoeuvring taps, and care for keeping taps closed when not being required.
5. *Dish washers and clothes washers:* recommendations under 8.4.1. (d) and (e) generally apply.
6. *Control of indoor leaks:* This includes
   - caring for detection and repair of leaks in pipes, plumbing fixtures and toilets,
   - using leak-proof fittings and other materials with specifications which correspond to pressures to be used as well as to the temperature of the water,
   - adopting good construction techniques and materials, as well as testing at the installation phase.

8.6. Water conservation and water saving in industrial and energy uses

Water conservation in industry and energy production mainly refers to the managerial measures and user practices that aim at preserving the water resources, essentially by combating the degradation of its quality. Water saving should be adopted in every managerial measure or user practice that aims at limiting or controlling the water demand and use for any specific process, including the avoidance of water wastes and the misuse of water.

In general, industrial processes and related support services have a large demand for water but, very often, the non-consumed fraction is very high and is returned to nature or to sewage systems. However, industrial demand is much smaller than the agricultural demand, particularly in arid and semi-arid regions (see Table 2.2), where it is of the same order of magnitude as the domestic demand except in tourist areas. On the other hand, in developed and industrialised regions, it largely exceeds the domestic demand. The great importance of the industrial water uses also result from the fact that they occur in populated areas, and are in

direct competition with domestic uses, and very often are supplied by the same urban networks.

The volumes and quality of water required by the industry vary with the type of industry and process. Similarly, the non-consumed fractions and the quality of effluents are also very different. Moreover, the same industry has different requirements for the quality of water to be supplied, and produces effluents with different qualities, which may require different treatment processes.

Water recycling and reuse are the main water saving processes in industry. Recycling consists in utilising water in the same process as it was originally used. The physical and chemical properties of the water may change after being used, requiring some simple treatment before being used again. Water reuse consists of using treated water after its use in a different process where it cannot be utilised again.

Water for energy production is generally not consumed, as for hydropower, though for evaporative cooling larger consumption is involved. However, in the latter case the disposed water may have higher temperature than required for some uses, including for nature in river ecosystems.

Water uses can be grouped in various ways in relation to water conservation and water savings as summarised in Table 8.8. The following are further considered:

(a) *Temperature control:* Water is used for both heating and cooling. The former usually involves the generation of steam in boilers that burn coal, oil, gas or waste products. Cooling processes employ the circulation of cold water through cooling towers, pipes or pools. Water conservation and savings concern, among others, the following issues:

1. Heating processes are generally in closed circuits and do not require high quality water, but mainly that the water does not produce detrimental residuals. The amount of residuals admissible depends upon the frequency and processes applied to clean the boiler. Treated water, inclusive of previous industrial uses, may be used. For steam production the recovery of water by condensation may be expensive but may be justified when water is scarce and could be reused.
2. Cooling requires water that has low temperature and is non corrosive or is not likely to attack the equipment or materials with which it is in contact. After cooling, the temperature of the water is elevated but can be recovered by open air-cooling and aeration, or be directly reused such as for greenhouse heating. Evaporative cooling towers consume quite large amounts of water. Evaporation losses are generally higher when cooling is practised in pools.

(b) *Manufacturing processes:* industrial processes requiring water are very diverse. Among the more important, water conservation and saving opportunities are:

1. Incorporation in the product, as is the case for drinking and food industries: extremely good quality water is required. The non-consumed fraction is small and may be added to reusable effluents.
2. Water used in physical extraction processes, such as in the vegetable oil industry, must be of high quality. However, effluents usually have too much organic inclusions but can often be reused for irrigation, such as the effluents from sugar cane mills.

TABLE 8.8. Issues in water conservation and water savings in industry

Water uses	Issues	Applicability and limitations
Industry		
Temperature control	More efficient recovery Recycling Reuse in other activities	Costly
Manufacturing processes	Reduced demand for water Adjust water quality to process requirements Replace water use processes by mechanical ones Recycling Reuse after treatment	Generally cost effective Effluents must follow water quality standards Penalties for polluting effluents
Washing	Use cleaning machines Avoid hose washing Water reuse	Investments required Effective
Indoor water uses	Devices to control discharges Care in use	As for indoor domestic water uses
Outdoor water uses	Water reuse Gardens with plants not sensitive to water stress Adopt micro-irrigation and water saving irrigation methods Use cleaning machines and avoid hose washing	Effective although it requires investments
General issues	Water metering	Control of water use Helps water saving programs
	Water quality monitoring	Control of recycling Control of water treatment Control of effluents for standards
	Leak detection and repair	Effective
Energy generation		
Hydropower	Integrated basin planning	Depending on water policies
Thermoelectric and nuclear	As for temperature control	Costly

3. When chemical extraction processes are used, the water quality requirements are related to the chemicals utilised, the type of raw material, and the type of manufactured product. Generally, water savings relate to changes in the processes and water conservation to the treatment of effluents, as is the case for the paper industry.
4. Textile dyeing requires huge amounts of water and reuse is limited due to difficulties in removing the dye. Water conservation in this industry depends upon further developments in research relative to that specific water treatment problem, such as is being pursued in China.
5. Washing raw food materials requires high quality water, which may be reused for cooling, heating or indoor washing if the size of the industry is large enough to reuse the water. Otherwise, effluents may be treated for external reuse.
6. Washing raw non-food materials generally do not require high quality water such as in the mining industry. Recycling may be adopted when effluents mostly carry

materials in suspension, which could be easily filtered. In this case, sedimentation ponds may be used for final treatment.

7. Water used for transportation of materials, in pipes or channels, requires variable water quality according to the nature of material to be transported, being generally high water demanding. Water demand is reduced when mechanical transport is adopted, and when recycled water could be used.
8. Water is also used for cooling equipment such as in wood and stone cutting and polishing industry. Water quality requirements relate then to not having materials in suspension nor corrosive chemical components. Generally water savings depend on advances in the equipment itself. Effluents often require extraction of sediments produced during the processes of cutting and polishing the materials.
9. In the construction industry water uses include incorporation in the product such as in concrete and other masses, cooling of stone and mosaic cutting equipment, and earth compaction. Non-saline water should be used. Water savings mainly concern the control of leaks from tanks and pipes utilised, and care in handling them to avoid unnecessary wastes.

(c) *Power generation:*

1. Water energy can be directly used to generate electrical energy by running turbines, so the water used is not consumed. However, water storage is often required, which may create a competition with other uses when the stored water could be used by other sectors. This problem can only be solved under a water conservation perspective when water resources are planned and managed at the basin scale adopting an integrated perspective, which needs to include allocation of the resource under competitive demand and multiple uses of stored water from reservoirs.
2. When reservoirs are required for energy production, losses by evaporation occur, as well as deep percolation. The latter is mainly controlled at construction. Evaporation losses are extremely difficult to control since the application of chemicals on the water surface may affect aeration of the water and is often detrimental for other uses, such as fish production, human consumption and recreational and environmental uses, which are common in these reservoirs.
3. Water is used in thermoelectric and nuclear plants for cooling. A large fraction of the water used is consumed because it vaporises, while another fraction is recovered by condensation and returned to nature, preferably after lowering its temperature. It could also be reused for heating in a different activity, such as greenhouse heating.

(d) *Washing*. A large variety of industrial residuals and other materials accumulate every day on the floors of industrial installations and buildings, as well as dust on the industrial equipment. Cleaning by washing is common. Water savings may be achieved in several ways:

1. Using dry cleaning machines when residuals and the floor are mostly non wet.
2. Using water cleaning machines, which require less water and detergent than water cleaning with a hose.
3. Separating heavily polluted washing effluents, such as with oils, from less polluted effluents. The first may not be reused while the latter may be reused in washing the floor.
4. Dry clean outside areas such as sidewalks and parking lots.

(e) *Water use in toilets, hand washing basins, showers, kitchens, and other services*: see the corresponding items in sections 8.4.1. and 8.5. relative to indoor water uses.

(f) *Outdoor water uses*: see the corresponding items in sections 8.4.2. and 8.5.

Recycling, reuse, and demand reduction in industry needs appropriate planning. To develop and implement such a plan requires (Duarte and Neto, 2001):

- appropriate knowledge on the industrial processes and respective operational fluxes,
- understanding and characterising the fluxes of residuals, mainly those of effluents, and including those from supporting activities such as bathing, kitchens and others,
- measuring the volumes of water used both in the industrial processes and in other indoor and outdoor activities, and assessment of the quantities and quality of effluents produced,
- identification of procedures that lead to minimise the effluents produced,
- identification of processes where recycled water may be used,
- identification of processes and activities where treated water may be used,
- revision of the technologies adopted and modernisation of processes used,
- selecting technologies for recycling and for water treatment,
- performing an economic evaluation of alternatives to select the one to be adopted.

Water metering is essential for implementing and managing a water saving program in industry. Metering is required to determine the water used and consumed in the main processes and globally, adopting a time step for evaluation from the hour to the month according to the type and size of the industry. Metering helps to evaluate how efficient are the processes adopted and for the water saving program itself, how and where to introduce improvements, and how to more easily involve and motivate the employees in saving water.

Monitoring the water quality is required to evaluate the efficiency of recycling and reuse treatments, and to evaluate the introduction of any modification in the respective processes that could be necessary. Monitoring is also necessary for the treatment of effluents that are to be rejected, which should respect target standards of quality, as is compulsory when the "polluter pays" principle is applied for rejections of inferior quality water.

As for other urban water uses, leak detection and repair assumes an important role in industry, particularly when large water uses are required, and recycling, reuse and water treatment are practised.

8.7. Water conservation in dryland agriculture

8.7.1. Introductory concepts

Dryland agriculture, also called dry farming or rainfed agriculture, is crop production without irrigation. Crop water requirements are satisfied by the rainfall occurring during the crop season. However, distinction should be made between rainfed agriculture in areas where rainfall is abundant, in humid and temperate climates, and crop production in water scarce regions where rainfall is low and erratic in quantity and temporal distribution and evapotranspiration largely exceeds precipitation during much of the year. The terms dryland agriculture and dry farming apply to the latter.

Dryland agriculture is traditionally practised in water scarce areas when rainfall during the rainy season is sufficient for the crop to develop and produce. Yields are commonly lower than for irrigated agriculture and vary in a large range from one year to the other, following the trends in the temporal variation of precipitation. The use of water conservation practices is usually required for successful crop production under water scarcity conditions.

Water conservation in dryland agriculture may assume quite different facets and include the selection of crops that are less affected by rain water deficits, the adoption of cropping practices that favour the ability of crops to escape water stress, and soil management practices that help to conserve water in the soil for crop use. A recent review has been produced by Unger and Howell (1999). In semi-arid and arid conditions and when drought occurs the water deficit periods during the crop season may be quite large, and supplemental irrigation and water harvesting become part of dry farming practices.

Typically, the term water conservation in dryland agriculture is used for the technologies which aim to improve the amount of water infiltrated and stored in the soil. However it is used here to include other technologies that improve the water productivity of the crops, i.e. the yield quantity produced per unit quantity of water. In fact, by increasing water productivity the water use is improved and the resulting demand for water may be better controlled and, in certain cases, the demand for other water uses may be better satisfied.

8.7.2. Crop resistance to water stress and water use efficiency

In dryland agriculture, crops and crop varieties are selected taking into consideration their tolerance to the water stress conditions that characterise the environments where they are cultivated. In general, these crops correspond to centuries of domestication of plants native to these environments, but new varieties have been introduced in the last decades following scientific plant breeding and improvement programmes. The most common food crops are wheat, barley and millet among cereals, and beans, cowpea and chickpea as legumes (pulses), as well as mustard and sunflower.

A summary of the mechanisms of crop resistance to water stress according to the nature of physiological and morphological processes and characteristics involved is presented in Table 8.9. The term drought resistance is commonly used by plant breeders and physiologists. It is also used here to describe the water stress mechanisms. However, the word drought is not used with the same meaning as defined in chapter 2 to describe a temporary anomaly in the water regime. These resistance mechanisms refer to three main groups: drought escape, drought avoidance and drought tolerance.

Drought escape corresponds to plant physiological characteristics typical of arid environments that make plants escape from prolonged periods of water stress, as is the case for plants that develop very fast and have a quite short biological cycle, or that have morphological characteristics that favour reduced impacts of insufficient water availability. These characteristics are common to natural herbaceous plants and shrubs in arid areas but they are rarely domesticated and seed yields are generally small. However, looking for these traits in varieties of cultivated crops is important to develop cultivated varieties less sensitive to drought water stress.

Drought avoidance consists of plant characteristics that provide for reduced transpiration and improved conditions to extract water from the soil. Reduced transpiration is naturally produced by a reduced number and size of stomata, control of the opening of

stomata in relation to the available water, small surface of leaves, reduced leaf exposure to solar radiation, leaf pubescence, leaf waxiness and cuticles. All these characteristics increase the resistance of water vapour transfers from the plant to the atmosphere and therefore reduce evapotranspiration. However, since photosynthesis is affected, yields are also reduced. Better capabilities to extract water from the soil are associated with more developed and deeper root systems, that may attain several metres in steppe shrubs, and higher water potential adjustment favouring the water fluxes from the soil to the roots and then to the leaves. Several of these traits are currently used in plant improvement programs including for pastoral areas.

TABLE 8.9. Drought resistance mechanisms, traits and benefits for crops to cope with water scarcity

Mechanism	Traits	Benefits
Drought escape		
▪ Rapid phenological development	▪ Short biological cycle	▪ Reduced seasonal crop water requirements
▪ Development plasticity	▪ Special morphological characteristics	▪ Lower reduction in seed numbers
Drought avoidance	▪	▪
Reduction of water losses:	▪	▪
▪ High stomatal resistance	▪ Size, number and opening of stomata	▪ Reduced transpiration
▪ Reduced evaporative surface	▪ Leaf rolling, smaller and fewer leaves, senescence	▪ Reduced transpiration and less radiation absorbed
▪ Low radiation interception	▪ Leaf pubescence and leaf orientation	▪ Higher reflectivity and less radiation absorbed
▪ High leaf cuticle resistance	▪ Thicker and tighter leaf cuticles, and waxiness	▪ Lower transpiration, and lesser dissecation effects
More efficient water extraction from the soil:		
▪ Larger root depth and density	▪ More extensive and intensive rooting	▪ Lower resistance for water uptake by the roots
▪ Larger liquid phase conductance	▪ More or larger xylem in roots and stems	▪ Lower resistance to water fluxes from roots to leaves
Drought tolerance		
▪ Ability to maintain turgor of cells	▪ Water potential kinetics and cell characteristics	▪ Decrease osmotic potential in response to stress
▪ Tissue water capacitance	▪ Favourable water potential kinetics	▪ Ability to maintain the daily water balance
▪ Dissecation tolerance	▪ Protoplasmic and chloroplast conditions	▪ Maintaining photosynthetic activity
▪ Accumulation of solutes	▪ Abscissic acid, ethylene, and others	▪ Regulation of leaf senescence and abscission

Drought tolerance consists of plant characteristics that make them able to cope with water deficits and include adjustments in cell turgor, capabilities to retain water in the tissues, maintaining photosynthesis despite transpiration being reduced, and controlling the senescence and abscission of leaves, as is the case for many shrubs in arid areas. Again, because transpiration is reduced photosynthesis is also decreased and plant yields are small. However these traits may be useful in plant improvement programmes.

Despite progress in plant breeding research, including genetic manipulation, results still are somewhat disappointing:

- The number of genes and characters with potential for altering the plant responses to water stress is too much large , thus making genetic manipulation difficult and only

slowly responsive. This is contrary to the success of plant improvement programmes focusing on resistances to given diseases or salinity, at least for some species.

- Benefits of plant responses to water stress are commonly contradictory to crop yield responses, i.e. a water stress resistant variety is able to yield regularly with less water use than other common varieties of the same crop but yields less than a more sensitive variety. This behaviour creates additional difficulties for plant breeding and improvement programs since the yield potential has to be considered. Moreover, the fact that varieties resistant to water deficit are less productive than more common varieties makes it difficult to get them adopted by farmers.
- Crop responses to water stress are influenced by other environmental factors such as wind and temperature, as well as by the cropping conditions (Wilkinson, 2000). Therefore, field tests to examine the resistance of crop varieties to water deficits are very demanding in both the setting up and evaluation of the experiments, and the tests are generally difficult to conduct.

Due to limitations of plant breeding programmes, research is also oriented to evaluate water use efficiency, i.e. the harvestable yield per unit water consumed, and the water productivity, i.e. the yield per unit water used (see section 8.2.1 for concepts) of crops commonly used in arid and semi-arid zones. An example of water yield performance of several crops is presented in Table 8.10. These experiments often combine the assessment of water yield performances with the evaluation of improved crop management techniques and practices such as fertilising and soil tillage practices. Among other important practices are those relative to planting dates and water conservation. Yield responses to supplemental irrigation are also considered when irrigation water may be available during the critical periods for crop water stress.

TABLE 8.10. Water use efficiency (WUE) for selected crops (adapted from Tarjuelo and de Juan, 1999).

Crop		WUE (kg yield/ m^3 water)	Crop		WUE (kg yield/ m^3 water)
Winter Grains	Wheat	1.8	Legumes	Alfalfa	1.2
	Barley	1.9		Chickpea	1.6
	Oats	1.7		Cowpea	1.8
Summer grains	Maize	2.9		Guar	1.9
	Sorghum	3.3		Navy bean	1.5
	Millet	3.7		Soybean	1.4
Rice		1.5	Fiber	Cotton	1.8
Roots	Potato	1.7		Flax	1.3
	Sugar beet	2.7	Sunflower		1.8

For small grains, data in Table 8.10 shows that barley reacts better than wheat to water conservation programmes but differences are not extreme. However, the advantages for barley increase when salinity stress is also considered. Differently, when comparing the water use performances of maize, sorghum and millet, the advantages for millet and, to a lesser extend, for sorghum are evident. Moreover, it can be observed that the most common crops traditionally used by farmers in the semi-arid and arid zones of the Middle East and North Africa are among the best performing crops listed in Table 8.10.

Reducing water consumption by crops cannot be an objective of water saving or water conservation because this would mean a reduction in plant transpiration and, therefore, a reduction in photosynthesis and biomass production, which is approximately proportional to transpiration. A reduction in crop consumption is therefore only acceptable under drought

conditions as a way to minimise crop production losses. An alternative approach would be to use plant breeding and genetic manipulation of plants aiming at improved drought resistance. In this approach the plant traits which contribute to reduced transpiration are sought in the genetic material utilised.

Instead of attempting to reduce the water consumption of a crop, water conservation and water saving programmes consider the selection of crops, crop varieties and crop patterns that consume less water than others. In particular, this may be achieved by looking for those crops and crop patterns that lead to higher water productivity and to the selection of crop and irrigation practices that provide for reducing the water use, i.e., that provide for better control of the non-beneficial water uses and the non-consumed fraction of water use as discussed in Section 8.2.2 (see Table 8.3). These aspects are discussed below.

8.7.2. Crop management

Water conservation in dryland agriculture mainly refers to crop management techniques and to soil management practices. Techniques for crop management to cope with water scarcity are summarised in Table 8.11. They relate to three main approaches:

(a) *Techniques to manage crop risk,* which concern crop management techniques designed to minimise the risks of crop failure and to increase the chances for beneficial crop yield using the available rainfall. They refer to:

1. The selection of crop patterns taking into consideration the seasonal rainfall availability and the water productivity of the crops and crop varieties. Here the aim is to lower the water stress effects on crop development and, therefore, to reduce impacts on yields, including under drought conditions. This approach provides high effectiveness in coping with water scarcity.
2. The adoption of water stress resistant crop varieties instead of high productive but more sensitive ones particularly when there is the possibility of a drought.
3. The use of short cycle crops or crop varieties, thus having smaller crop water requirements than varieties or crops with longer growth seasons.
4. To adapt planting dates such as to plant after the onset of the rainy season to ensure more effective conditions for crop establishment.
5. Early seeding to avoid terminal stress of the crop.
6. Early cutting of forage crops to avoid the degradation of the stressed crop.
7. Grazing drought damaged field crops to permit an alternative use of the biomass for livestock when the yield is lost due to drought damage.
8. To adopt supplemental irrigation of dryland crops at critical crop growth stages to avoid loosing the crop yield when a drought occurs. This can be a highly effective technique when water may not be enough to adequately irrigate a dry season crop.

(b) *Controlling the effects of water stress* by adopting techniques and practices that reduce the impacts of water deficits on crop development and yield. These include:

1. The use of soil management techniques that provide for increasing the available soil water, as discussed in Section 8.7.3, below.
2. The adaptation of crop rotations to the environmental constraints and resource conservation, namely including several years with covered fallow for grazing, as commonly practiced in the Mediterranean region and Australia.

TABLE 8.11. Techniques for crop management to cope with water scarcity

Crop management techniques	Benefits	Effectiveness
Crop risk management		
▪ Selection of crop patterns taking into consideration the available season rainfall and the crop water productivity	▪ Lesser water stress effects, including under drought	▪ High
▪ Choice of water stress resistant crop varieties when drought and high water deficiency are likely	▪ Lesser impacts on yields	▪ High (under drought)
▪ Use of short cycle crops/varieties	▪ Lesser crop water requirements	▪ High
▪ Planting after the onset of the rainy season	▪ Ensure crop establishment	▪ High
▪ Early seeding	▪ Avoidance of terminal stress	▪ Variable
▪ Early cutting of forage crops	▪ Avoiding the degradation of the stressed crop	▪ Limited
▪ Grazing drought damaged fields	▪ Alternative use for livestock when grain yield is lost	▪ Limited to drought only
▪ Supplemental irrigation of dryland crops at critical crop growth stages	▪ Avoid loosing the crop yield when a drought occurs	▪ High
Controlling effects of water stress		
▪ Use of appropriate soil management techniques	▪ Increase available soil water	▪ High
▪ Adaptation of crop rotations to the environmental constraints, namely to include covered fallow for grazing	▪ Coping with water stressed environment	▪ High
▪ Include a tilled bare soil fallow in the crop rotation	▪ Increase in soil moisture	▪ Variable
▪ Use of mixed cropping and inter-cropping, namely for legumes	▪ Better use of resources	▪ Variable
▪ Adopt large plant spacing of perennials (tree crops), large row spacing for annual crops, and low density seeding for cereals	▪ High exploitable soil volume by tree or plant, increased available soil water	▪ High
▪ Reduced fertiliser rates	▪ Adaptation to reduced yield potential and minimising salt effects	▪ Variable
Water conservation cropping techniques		
▪ Conservation tillage	▪ Control of soil evaporation losses	▪ High
▪ Adequate seed placement	▪ Prevention of rapid soil drying around the seed	▪ High
▪ Seed placement in the furrow bottom and planting in soil depressions	▪ Place root systems where soil moisture is better conserved	▪ High
▪ Pre-emergence weed control	▪ Alleviating competition for water, avoiding herbicide effects on crop	▪ Variable
▪ Early defoliation	▪ Decrease crop transpiration surfaces and use leaves for animal feeding	▪ Limited
▪ Windbreaks	▪ Decrease wind impacts on evaporation,	▪ Variable
▪ Anti-transpirants and reflectants	▪ Reduction of plant transpiration	▪ Costly
▪ Growth regulators	▪ Control physiological processes in relation to water availability	▪ Costly and difficult
▪ CO2 enrichment (controlled environments)	▪ Increased yields per unit of water consumed	▪ Limited and costly

3. The inclusion of a bare tilled soil fallow period in the crop rotation in order to control soil water losses and provide for enough soil moisture at crop planting.
4. The use of mixed cropping and inter-cropping with legumes (pulses) to better use the available soil and water resources.
5. The adoption of large plant spacings for perennial crops, mainly tree crops, as is widely practiced for olives in North Africa and the Middle East, thus providing for a large soil volume to be explored by the crop roots in low rainfall areas.
6. Using large row spacing for annual crops and low density seeding for cereals, also to increase the soil volume exploitable by each plant.
7. Reducing the fertiliser rates when a low yield potential is predicted, which not only reduces costs but also minimises the effects of salt concentration in the soil.

(c) *Water conservation cropping techniques,* designed to increase the available soil water, to control soil water losses by evaporation, to minimise the transpiration by weeds and their competition for water, as well as to reduce crop transpiration when water stress is extreme. These water conservation techniques and practices include:

1. Conservation tillage, which may be highly effective for increasing soil infiltration and controlling soil evaporation losses as discussed in the next Section.
2. Adequate seed placement to prevent rapid drying of the soil around the seed.
3. In arid climates, seed placement in the furrow bottom and planting in soil pits, thus providing for the development of the root systems where infiltration is higher and soil moisture may be better conserved.
4. Adoption of appropriate weed control to alleviate competition for water and transpiration losses by weeds. Adopting pre-emergence treatments avoids herbicide effects on stressed crop plants as may happen with later treatments.
5. Adopting delayed fertilisation may favour root development while splitting the applications improves fertilisers use and helps to control their residual accumulation in the soil and further leaching and transport to the groundwater when excess rainfall infiltrates.
6. Adopting early defoliation to decrease the leaf area contributing to transpiration, which is a traditional practice in water scarce areas, especially where leaves can then be used as fodder for livestock.
7. Using windbreaks that, in addition to controlling wind stress on the crops, decrease evaporation, particularly when advective conditions prevail.
8. Using anti-transpirants to reducing plant transpiration, reflectants to decrease the energy available for transpiration by increasing the fraction of the incoming solar energy that is reflected by the crop canopy, and growth regulators to adjust the plant physiological processes to the water availability. Besides being expensive, they are difficult to use effectively in practice.
9. CO2 enrichment in controlled environments. This can increase the photosynthetic activity of plants in respect to respiration, thus providing for higher yields per unit of water consumed. However, this practice has low effectiveness in field applications.

8.7.3. Soil management

Soil management practices for water conservation refer to tillage and land-forming practices

that favour rainfall infiltration into the soil, water storage in the soil zone explored by roots, capture of runoff to infiltrate the soil, control of evaporation losses from the soil and weeds, extraction of water by plant roots, and crop emergence and development.

These practices have long been known to have positive impacts on water conservation in dryland farming. However, results of any soil management technology depend upon the soil physical and chemical characteristics, the land-forms and geomorphology, the climate and the kind of implements used. All these factors interact, creating variable responses in terms of crop yields. When a technique is to be introduced in a given environment and it is substantially different from the traditional and well-proved practices adopted by local farmers, it is advisable to perform appropriate testing before it is widely adopted. However, the principles of soil management for water conservation are of general application, regardless of the size of the farm, the traction used, or the farming conditions.

Soil management practices for water conservation, are often common to the practices for soil conservation, i.e. they not only provide for augmenting the soil moisture availability for plant growth but they also contribute to the control of erosion and soil chemical degradation. In many cases they contribute to improving the soil quality. Because these practices produce changes in soil infiltration rates and amounts, soil water storage and runoff volumes, they may also produce relatively important changes in the hydrologic balance at the local field scale and, when widely adopted, they may affect the hydrologic balance at the basin scale.

The soil management practices for water conservation, summarised in Table 8.12, can be grouped as follows:

(a) *Runoff control and improved water retention on the soil surface* to provide for a higher amount of rainwater that can infiltrate into the soil and a larger time opportunity for the infiltration to occur. These effects are produced by creating a higher roughness of the cropped land where slopes are flat, but do not apply to sloping landscapes, which are discussed later. Practices, many of them traditionally used in dry farming, include:

1. Soil surface tillage, which concern shallow cultivation tillage practices to produce an increased roughness on the soil surface permitting short time storage in small depressions of the rainfall in excess to the infiltration, i.e. limiting overland-flow to give a larger time opportunity for infiltration. This practice is effective for very low sloping land cropped with small grains in soils having good stability of aggregates.
2. Contour tillage, where soil cultivation is made along the land contour and the soil is left with small furrows and ridges that prevent runoff formation and create conditions for the water to be stored until infiltration can be completed. This technique is also effective to control erosion and may be applied to row crops and small grains provided that field slopes are low. When rain could create waterlogging graded furrow tillage across the slope may be more helpful than contour tillage.
3. Using mulches from crop residues or straw applied on the soil surface, which also increases surface roughness which slows the overland-flow and, in addition, improves soil infiltration conditions as mentioned below.
4. Furrow diking to permit the storage of rain water in small basins or pits created along the furrows, which is also particularly useful in sprinkler irrigated furrows to avoid runoff and store the excess applied water until infiltration is completed. This practice is highly effective for sprinklers on moving laterals that often apply water at rates

TABLE 8.12. Soil management techniques for water conservation in agriculture

Soil management techniques	Benefits	Effectiveness
Water retention on the soil surface and runoff control		
▪ Soil surface tillage for increased surface roughness	▪ Ponding of rainfall excess in depressions, larger time opportunity for infiltration	▪ High (flat lands)
▪ Tillage for contour (and graded) furrows and ridges	▪ Runoff and erosion control, storage in furrows, increased time for infiltration	▪ High (low slopes)
▪ Residues and crop mulching	▪ Runoff retardation and higher infiltration	▪ High (low slopes)
▪ Furrow dikes	▪ Rain water storage in furrow basins/pits and increased infiltration amounts	▪ High
▪ Bed surface cultivation	▪ Runoff control and increased infiltration	▪ Variable
Increasing soil infiltration rates	▪	
▪ Organic matter for improving aggregation	▪ Improved soil aggregates and increased infiltration	▪ High to very high
▪ Conservation tillage	▪ Preserve soil aggregates and infiltration rates	▪ High to very high
▪ Mulches, crop residues	▪ Soil surface protection, better aggregates and higher infiltration rates	▪ High to very high
▪ Traffic control	▪ Less soil compaction and improved water penetration in the cropped area	▪ Variable
▪ Chemicals for aggregates	▪ Favours soil aggregates and infiltration rates	▪ Medium to high
Increasing the soil water storage capacity		
▪ Loosening tillage	▪ Increased soil porosity, soil water transmission and retention	▪ High
▪ Subsoiling to open natural or plough made hardpans	▪ Improved soil water transmission and storage, and increasing the soil depth exploitable by roots	▪ High to very high
▪ Deep tillage/profile modification in clay horizons	▪ Increased water penetration and soil depth exploitable by roots	▪ High but costly
▪ Chemical and physical treatments of salt-affected soils	▪ Increased infiltration and available soil water	▪ High to very high
▪ Hydrophilic chemicals to sandy/coarse soils	▪ Increase water retention in the soil profile	▪ Economic limits
▪ Mixing fine and coarse horizons	▪ Increase water transmission and retention	▪ Economic limits
▪ Asphalt barriers in sandy soils	▪ Decrease deep percolation	▪ Limited, costly
▪ Compacting sandy soils	▪ Control of deep percolation, higher retention	▪ Variable
▪ Control of acidity by liming, and of salinity by gypsum	▪ More intensive and deep rooting, and improvement of aggregation	▪ High
Control of soil evaporation		
▪ Crop residues and mulching	▪ Decrease energy available on soil surface for evaporation	▪ Very high
▪ Shallow tillage	▪ Control soil water fluxes to the soil surface	▪ High
▪ Chemical surfactants	▪ Decrease capillary rise	▪ Economic limits
Runoff control in sloping areas	▪	
▪ Terracing, contour ridges and strip cropping	▪ Reduced runoff, increased infiltration, and improved soil water storage	▪ High to very high
Water harvesting (arid lands)	▪	
▪ Micro water-harvesting	▪ Maximise rainfall infiltration at plant scale	▪ High to very high
▪ Micro-watersheds	▪ Maximise runoff collection at tree scale	▪ High to very high
▪ Runoff farming	▪ Maximise runoff collection at field scale	▪ High to very high
▪ Water spreading	▪ Maximise the use of flood runoff through diversion for infiltration in cropped fields	▪ High to very high

higher than the soil infiltration rate. However the effectiveness of this method depends upon the slope of the furrows and of the land.

5. Bed surface profile, which concerns cultivation on wide beds and is typically used for horticultural row crops. Often beds are permanent and traffic is only practiced in the furrows between beds, which should follow the land contours. The soil aggregation and infiltration are kept undisturbed on the bed and water is captured, stored and infiltrated into the furrows.

(b) *Improvement of soil infiltration rates*, which refer to a variety of practices that aim at increasing water penetration into the soil and maintaining high rates of infiltration. This limits the rain water that may run off or that evaporates when stored at the soil surface. These practices refer to:

1. Increasing or maintaining the amount of organic matter in the upper soil layers because this provides for better soil aggregation, which is responsible for the macropores in the soil. Organic matter also preserves soil aggregates, avoiding crusting or sealing at the soil surface, which closes soil pores and significantly decreases the infiltration rates. Maintaining the continuity of macropores through which water penetrates and redistributes within the soil profile is essential.
2. Conservation tillage, including no-tillage and reduced tillage, where residuals of the previous crop are kept on the soil at planting. Mulches protect the soil from direct impact of rain drops, thus controlling crusting and sealing processes resulting from dispersion of aggregates by the rain drop impacts. Conservation tillage also helps to maintain high levels of organic matter in the soil. The soil is also less disturbed by tillage operations which for silty soils, could affect soil aggregates. Therefore, conservation tillage, which is now practised world-wide, is highly effective in improving soil infiltration and controlling erosion in dryland farming.
3. Application of mulches in tree and shrub fruit crops, or use of weed residuals when orchards are not tilled, to improve soil infiltration similar to the processes described above. The effectiveness of this technique is particularly relevant for tropical soils where organic matter is rapidly mineralised and rains may be very intense.
4. Traffic control, i.e. adopting permanent paths for tractors and other equipment, thus limiting soil compaction to these zones, which improves water penetration in the remainder of the cropped area.
5. Application of chemical additives to the soils for strengthening the soil aggregates, thus avoiding soil sealing, and to preserve soil porosity and water pathways in the soil. These may be highly effective for improving infiltration conditions in soils with less stable aggregates.

(c) *Increasing the soil water storage capacity* by improving the soil water holding characteristics, increasing the depth of the soil root zone, or favouring soil water conditions for water extraction by plant roots. Several practices may be considered:

1. Loosening tillage, which is applied to naturally compacted soils such as heavy silt soils, or to soils compacted by frequent tillage operations and traffic of tractors and equipment. It provides for increased soil porosity, thus enhancing conditions for water transmission and retention in the soil. Conditions for root development are also improved. This technique has variable effectiveness and often has to be repeated quite frequently.
2. Subsoiling for destroying natural or plough made hardpans, which may significantly

improve conditions for water movement downwards and, consequently increase soil water storage. It also provides improved pathways for the roots to develop into deeper layers, thus enlarging the soil depth exploitable by crop roots. Overall, this practice may increase appreciably the amount of water stored in the soil that becomes available for crop use.

3. Deep tillage or soil profile modification when clay horizons overlay more coarse soil horizons. This mixing or even inverting of relative positions of layers, contributes for increasing infiltration, deepening of crop roots, improving the availability of soil water for crop use, and larger water storage volumes.
4. In cold regions, loosening the soil by refilling the soil water storage prior to the soil freezing season. Water changes in volume when freezing and melting occurs and increases soil porosity and as a result, infiltration and water retention in the soil profile.
5. Chemical and physical treatments of salt-affected soils, i.e. treating saline and sodic soils to reduce salt concentration and toxicity to plants. This treatment also provides for reducing the osmotic potential with consequent improvement in the availability of soil water for crops use. It also modifies the physical conditions for water penetration and movement in the soil, thus increasing infiltration, and favours the development of crop roots into deeper layers. Overall, the amount of water stored in the soil usable by crops can be greatly enhanced.
6. Adding fine materials or hydrophilic chemicals to sandy/coarse soils slows the water transmission downwards, increases water retention, controls deep percolation and therefore increases the availability of water in soils with natural low water holding capacity. Similarly, asphalt barriers in sandy soils may be used to decrease deep percolation, but their use is more costly and application is difficult.
7. Compacting coarse textured soils may help reduce infiltration and deep percolation but results are variable and uncertain.
8. Control of acidity by liming, similarly to gypsum application to soils with high pH. This treatment favours more intensive and deep rooting, better crop development and contributes to improved soil aggregation, thus producing some increase in soil water availability.

(d) *Control of soil evaporation*, which may be achieved in different ways:

1. Mulching with crop residues, straw, and several other materials including plastic and stones, which is aimed at decreasing the amount of energy available at the soil surface for soil water evaporation. Mulching, which shades the soil, also contributes to control of weeds and therefore of non-beneficial water use
2. Plastic mulching, as used for horticultural field crops to speed up crop emergence and the first stages of crop development, also provides for control of evaporation from the soil. This is particularly true for non transparent plastics that decrease net radiation available at the soil surface.
3. Shallow tillage, also called dust mulching or soil mulching, is a practice consisting of tilling the soil surface, only to a shallow depth, to create a discontinuity between the surface where energy is available and the deeper soil layers where water is retained and from where it would move upwards by capillarity if continuous pathways existed. Shallow tillage is a very common traditional practice in orchards and for the bare fallow period antecedent to crop planting. Besides its effects in directly

controlling soil evaporation, it also provides mechanical control of weeds, and therefore of their transpiration losses. Shallow tillage is highly effective when the high evaporation season is the dry season, i.e. when tillage can be performed before the high evaporation season.

4. Chemical surfactants that limit capillary upwards fluxes are also stated to have potential to limit soil water evaporation. However, there is not enough evidence on the effectiveness of this technique.

(e) *Runoff control in sloping areas,* which correspond to well known erosion control measures, also provide for water conservation in sloping landscapes. Most of them are associated with modifications of the land forms, reducing both the slope lengths and the slope angles. Generally they consist of:

1. Terracing, which may assume different forms as terraces are designed for both low slope lands cultivated by non-intensive field crops, or for medium to steep slopes, usually adopted for small farms. The first may be designed for infiltration of excess water in the downstream part of the cultivated area, as is common in low rainfall regions, or to drain off that excess water that may be stored in small reservoirs for use by cattle. The second may be designed to naturally drain excess water in the direction of the land slope, or may be designed to infiltrate most of excess water and then have horizontal or near horizontal surfaces. In every case, terraces slow down the overland flow and increase the amount of rainwater that can infiltrate the soil. In low rainfall areas only a small part of the storm rain flows out as runoff. Therefore, the amount of water that infiltrates the soil is significantly increased, mainly when terracing is associated with other soil management practices as described above.
2. Contour ridges, which correspond to a simplification of large terraces on low slope landscapes. Here the natural slope is divided by ridges along the contour lines at spacings which vary inversely with the slope angle. Ridges constitute obstacles to the runoff, that may be drained out by surface drains located immediately upstream of the contour ridges, or that may infiltrate from shallow ditches also located near the ridges. Alternatively, the land slope may be divided by stone walls that decrease the overland flow velocity and favour infiltration. As a result, whatever the solution that is adopted, runoff is controlled and the fraction of rainfall that infiltrates is increased.
3. Strip cropping, which is a technique for retardation of runoff and enhancing infiltration in low sloping areas. The land slope is divided into strips where different crops are cultivated using the contour tillage practice referred to above. Because different crops are used in successive strips they create different conditions for runoff and infiltration (particularly resistance to overland flow), that overall decreases the fraction of rainfall lost to the crops as runoff.

(f) *Water harvesting,* which are techniques used in arid lands to maximise the fraction of rainfall that is used for crops. Water harvesting, which is already analysed in Chapters 5 and 7, may have different forms that may be grouped as:

1. Micro water-harvesting, referring to a technique where planting is performed on the bottom of wide spaced furrows, so that the large surfaces between the ridges act as rainfall collection areas to maximise infiltration near the plants.
2. Micro-watersheds, where a fraction of the available area is used to collect the rainfall, which flows downslope to infiltrate into the cropped area. The ratio between the cropped area and the collection area generally decreases as the rainfall decreases.

3. Runoff farming, corresponding to techniques that maximise runoff from small areas, which is then stored in small reservoirs for supplemental irrigation or infiltrated in the cropped area.
4. Water spreading, also known as spate irrigation, which consists of diverting flood runoff to the cropped fields where it infiltrates.

The analysis above shows that there are a large variety of traditional and modern soil management practices for water conservation in dryland agriculture. Some of these practices are specific to given environments but others are of more general use, particularly mulching, which may be associated with conservation tillage, and organic matter incorporation. Many of these practices are for dryland farming only but some apply to irrigated agriculture. This is the case for the techniques that enhance soil water storage, that improve infiltration conditions or that help in controlling soil evaporation. A case study on soil management for improved water conservation in the North China Plain is presented in Box 8.2.

The analysis that follows, which refers to irrigated agriculture does not specifically mention most of the soil management practices but their consideration must be included when fully assessing strategies to improve water conservation and saving in water scarce agricultural ecosystems.

8.8. Water savings and conservation in irrigated agriculture

8.8.1. Demand management: general aspects

Demand management for irrigation to cope with water scarcity consists of reducing crop irrigation requirements, adopting irrigation practices that lead to higher irrigation performances and water saving, controlling system water losses, and increasing yields and income per unit of water used. It includes practices and management decisions of an agronomic, economic, and technical nature.

The objectives of irrigation demand management can be summarised as follows:

- *Reduced water demand* through selection of low demand crop varieties or crop patterns, and adopting deficit irrigation, i.e. deliberately allowing crop stress due to under-irrigation, which is essentially an agronomic and economic decision.
- *Water saving / conservation,* mainly by improving the irrigation systems, particularly the uniformity of water distribution and the application efficiency, reuse of water spills and runoff return flows, controlling evaporation from soil, and adopting soil management practices appropriate for augmenting the soil water reserve, which are technical considerations.
- *Higher yields per unit of water,* which requires adopting best farming practices, i.e. practices well adapted to the prevailing environmental conditions, and avoiding crop stress at critical periods. These improvements result from a combination of agronomic and irrigation practices.
- *Higher farmer income,* which implies to farm for high quality products, and to select cash crops. This improvement is related mainly to economic decisions.

BOX 8.2. Case study on soil management for improved water conservation

Experiments at two locations in the North China Plain, Daxing and Xiongxian, were developed to identify soil management issues for soil water conservation. The annual rainfall varies from near 330 mm to 700 mm. Rainfall is concentrated in July and August while during the winter wheat season it is only 17% of the annual total. The soils are very silty at both sites, containing more than 70% of silty particles, and have a poor non-stable structure. Salinity effects are negligible but soils have high pH. Soils have limited soil fertility and high exchangeable sodium percentage (ESP). Several soil treatments were compared and various soil properties and crop performance results were analysed (Ding and Hahn, 1998).

1. *Bulk density/soil compaction*: Subsoiling, i.e. subsurface tillage for soil loosening, significantly reduced the bulk density in the 20-40 cm layers but effects are reduced by the third year due to recompaction. Gypsum application also favoured lower bulk density.
2. *Soil aggregate stability*: Gypsum significantly increased aggregate stability.
3. *Soil chemical properties*: Soil pH decreased after gypsum application. The cation exchange capacity was greatly increased indicating better soil nutritional conditions. Exchangeable sodium percentage decreased very significantly, which favoured improved soil permeability and structural stability.
4. *Infiltration rate*: Subsoiling gave a consistently higher infiltration rate than the commonly practised disk harrow tillage and no tillage by breaking up the compacted plough pan. Gypsum addition increased the infiltration further throughout the season due to stabilising the soil structure.
5. *Water storage*: The soil water storage in the mulch treatment was higher than that in other treatments, mainly when the rainfall was lower than the average. Early in the season, it was observed that the soil surface under mulch remained moist for 10 days after rainfall, whilst in other areas, it became dry in 3 to 4 days. The cause is that straw mulch reduces evaporation from the soil. The no-tillage showed higher water content in the top layer (0-30 cm) three weeks after maize sowing.
6. *Crop emergence*: Mulch produced the highest emergence rates because it favoured the topsoil retaining moisture and controlled the formation of crusts on the soil surface.
7. *Summer maize roots*: Subsoiling tillage significantly increased root depths, length and mass, which improves the use of water stored in the soil.
8. *Summer maize yield*: Mulch produced the highest yield followed by subsoiling. For the soil with higher silt percentage, the best yields were obtained by associating subsoiling with mulch. These results indicate that changing the behaviour of the soil relative to water infiltration, storage and evaporation induces yield impacts in line with improvements in soil water availability.

The agronomic aspects of irrigation demand management refer essentially to those described in the previous chapter. They concern crop improvement relative to resistance to water stress and respective water productivity, cropping techniques that favour coping with lesser water availability, and soil management for water conservation. Economic decisions, not dealt with here, concern the decision making processes relative to the selection of crop patterns and farming practices that reduce the crop irrigation demand, and include the evaluation of the economic returns and feasibility of water saving and conservation practices. The technical aspects of demand management which concern the various practices within irrigation are dealt in this section.

Issues for irrigation demand management often refer only to irrigation scheduling, giving to irrigation methods a minor role. However, an integrated approach is required (Pereira, 1996; 1999). Irrigation scheduling is the farmers decision process relative to "when" to irrigate and "how much" water to apply at each irrigation. The irrigation method concerns "how" that desired water depth is applied to the field. The crop growth phase, its sensitivity to water stress, the climatic demand by the atmosphere, and the water availability in the soil determine when to apply an irrigation or, in other words, the frequency of irrigation. However, this frequency depends upon the irrigation method, i.e. on the water depths that are typically associated with the on-farm irrigation system. Therefore, both the irrigation method and the irrigation scheduling are inter-related.

Irrigation scheduling requires knowledge of crop water requirements and yield responses to water (cf. Allen *et al.*, 1998), the constraints specific to the irrigation method and respective on-farm delivery systems (cf. Pereira and Trout, 1999), the limitations of the water supply system relative to the delivery schedules applied, and the financial and economic implications of the irrigation practice. To improve the irrigation method requires the consideration of the factors influencing the hydraulic processes, the water infiltration into the soil, and the uniformity of water application to the entire field. Therefore, irrigation demand management to cope with water scarcity is discussed here with respect to both the irrigation systems and scheduling.

Several performance indicators are currently used in on-farm irrigation. The uniformity of water application to the entire field is commonly evaluated through the *distribution uniformity* (DU), which is the ratio between the average infiltrated water depth (mm) in the low quarter of the field and the average infiltrated water depth (mm) in the entire field (Burt *et al.*, 1997; Pereira, 1999). The distribution uniformity essentially depends upon the characteristics of the irrigation system and less on the farmer management. In other words, high DU can only be achieved when the farmers manage the irrigation system well and it is well designed and maintained, whilst poorly designed and/or maintained irrigation systems definitely lead to low DU (Pereira *et al.*, 2002).

The main farm efficiency indicator is the *application efficiency* (AE), the ratio between the average water depth (mm) added to root zone storage and the average depth (mm) of water applied to the field. AE is a measure of the quality of irrigation management by the farmer and is strongly related to the appropriateness of decisions on when and how much water is applied. Due to the limitations imposed by the system characteristics, the application efficiency depends upon the distribution uniformity. In general, when the distribution uniformity values observed are high, the application efficiencies will also be good when irrigation scheduling is appropriate.

Useful relations between irrigation uniformity and crop yields have been made available and may be helpful to practitioners (e.g. Warrick and Yates, 1987). These relationships show that attaining high DU is a pre-condition to achieve high application efficiencies, and therefore to obtain a good match between the amounts of water applied and the crop use requirements. Therefore, DU is an indicator that relates well to the system characteristics that favour water conservation and saving, as well as to higher water productivity. Therefore improvements in performance of farm irrigation methods and systems will be mainly discussed relative to their effects on distribution uniformity.

8.8.2. Demand management: improving surface irrigation systems

Several surface irrigation methods are used in practice. The main ones are:

- *Basin irrigation*, which is the most commonly used irrigation system world-wide. Basin irrigation consists of applying water to levelled fields bounded by dikes, called basins. Two different types are considered, one for paddy rice irrigation, where ponded water is maintained during the crop season, and the other for other field crops, where the ponding time is short, just until the applied volume infiltrates. For non-rice crops, basin irrigation can be divided into two categories: traditional basins, with small size and traditional levelling; and modern precision-levelled basins, which are laser levelled and have large sizes and regular shapes. Especially with traditional basins, shape depends on the land slope and may be rectangular in flat areas and follow natural land contours in steep areas. For row crops, and especially horticultural crops, the basins are often furrowed with the crops being planted on raised beds or ridges. For cereals and pastures, the land is commonly flat inside the basin. Tree crops sometimes have raised beds around the tree trunks for disease control. Basin irrigation is most practical when soil infiltration rates are moderate to low and soil water holding capacity is high so large irrigations can be given. Basin irrigation depths usually exceed 50 mm. Inflow rates for basin irrigation have to be relatively high (> 2 l s^{-1}per meter width) to achieve quick flooding of the basin and therefore provide for uniform time of opportunity for infiltration along the basin length. Basins must be precisely levelled for uniform water distribution, because basin topography determines the recession of the ponded water.
- *Furrow irrigation*: water is applied to small and regular channels, called furrows, which serve firstly to direct the water across the field and secondly act as the surface through which infiltration occurs. There is a small discharge in each furrow to favour water infiltration while the water advances down the field. Furrow irrigation is primarily used for row crops. Fields must have a mild slope, and inflow discharges must be such that advance is not too fast, nor too slow, i.e. the time elapsed since inflow starts at the upstream end until the water arrives to the other end must be in equilibrium with the infiltration to avoid either excess runoff at the downstream end, or excess infiltration in the upstream zone. Efficient furrow irrigation nearly always requires irrigation times longer than advance times. Runoff at the downstream end typically varies from 10 to 40% of the applied water, which should be collected, stored, and reused. Irrigation furrows are usually directed along the predominant slope of the field. Furrows are used on slopes varying from 0.001 m m^{-1} to 0.05 m m^{-1}. Low slopes require soils with low infiltration rates. Slopes greater than 0.01 m m^{-1} usually result in soil erosion.
- *Border irrigation*: water is applied to short or long strips of land, diked on both sides and open at the downstream end. Water is applied at the upstream end and moves as a sheet down the border. Border irrigation is used primarily for close growing crops such as small grains, pastures, and fodder crops, and for orchards and vineyards. The method is best adapted to areas with low slopes, moderate soil infiltration rates, and large water supply rates. Borders are most common and practical on slopes less than 0.005 m m^{-1} but they can be used on steeper slopes if infiltration is moderately high and the crops are close growing. Irrigation to establish new crops on steep borders is difficult because water flows quickly, is difficult to spread evenly, and may cause erosion. Design and management of very flat borders approximates conditions for level basins. Precise land levelling is required, and inflow rates should be neither erosive, nor producing too slow

or too fast advance.

Farm irrigation systems may be distinct according to their degree of modernisation. In traditional systems, the water control is carried out manually according to the ability of the irrigator. In small basins or borders and in short furrows, the irrigator cuts off the supply when the advance is completed. This practice induces large variations in the volumes of water applied at each irrigation, and it is difficult to control "how much" water is applied. Over-irrigation is then often practised. In modernised systems, some form of control of discharge and of automation is used. The fields are often precision levelled, and the supply time and the inflow rate can be known and controlled. In modernised systems it is much easier than in traditional systems to control "how much" water should be applied, which favours the adoption of controlled and reduced irrigation demand.

In surface irrigation, the distribution uniformity, DU, mainly depends upon the system variables controlling the water advance along the field and the way in which the water is distributed and infiltrates throughout the field. These variables include the inflow discharge, field length and slope, uniformity of the land surface topography in relation to land levelling conditions, and the duration of water supply to the field. The application efficiency, in addition to these variables, is influenced by the soil water deficit at the time of irrigation. The farmer's skill plays a major role in controlling the time duration of water application, in applying the water at the appropriate soil water deficit and in maintaining the system in good operational conditions. However, his capability to achieve higher performances is limited by the system characteristics and, often, by the delivery rules relative to supply timing, duration and discharges, which are dictated by the canal network managers. Therefore, under these circumstances, adopting improved scheduling and management rules is often beyond farmers decisions and ability because the off– and on-farm system limitations are often the prime constraint.

Improvements in surface irrigation systems that help to cope with water scarcity are numerous and depend upon actual field conditions. They relate to improvements in water advance conditions, increased uniformity of water distribution in the entire field, easy control of the water depths applied, and reducing deep percolation and runoff return flows. These improvements are briefly referred to in Table 8.13, where benefits expected and common limitations for implementation are also included. Benefits generally relate to irrigation performances, mainly DU and AE as analysed above, and to the water productivity (WP) defined in Box 8.1. The ease of control of the required leaching fraction (LF) when using saline waters or irrigating saline soils, discussed in Section 7.3, is also considered because the application of a leaching fraction is commonly necessary in arid and semi-arid climates where the seasonal rainfall is insufficient to produce natural leaching of salts.

Improvements in surface irrigation systems aimed at reducing the water volumes applied and increasing the water productivity to cope with water scarcity can be grouped as follows:

(a) *Land levelling,* which is a very important practice to improve surface irrigation performances. It provides conditions for reducing the advance time and water volumes required to complete the advance, better water distribution uniformity (DU) and application efficiency (AE), as well as better conditions for adopting deficit irrigation and easier control of the required leaching fraction (LF). This technique is easy to apply in large farms, including precision levelling as a maintenance procedure, but requires appropriate support when it is to be applied in small farms.

(b) *Irrigation with anticipated cut-off,* i.e. cutting the inflow to basins or borders before the advance is completed, or to furrows before the downstream area is irrigated. This technique reduces water application volumes but the last quarter or half of the field is often under-irrigated or, as for furrows, just rainfed. It avoids runoff and minimises percolation. This practice is easily applicable under conditions of limited water availability but may have important impacts on yields and economic returns.

(c) *Field evaluation,* which consists of monitoring irrigation events in farmers' fields. It does not provide water savings by itself but produces detailed information to the farmers and extension staff that permit the selection and further adoption of corrective measures. It can provide basic information for controlling percolation and runoff, improving DU and AE, and adopting water saving practices, as well as improving the timeliness and duration of irrigation events leading to better system management and salinity control. Appropriate field monitoring programmes need to be implemented. Field evaluations play a fundamental role in improving surface irrigation systems, as they provide information for systems design and, mainly, for advising irrigators on how to improve their systems and practices.

(d) *Improved design and modelling.* As for field evaluation, it does not produce water savings but provides for it through the selection of the best combination of field sizes, slope, inflow discharges and time of application that optimise conditions for controlling deep percolation, runoff, leaching fraction applications, and deficit irrigation. It requires support by extension services and should be based on data from field evaluation and monitoring programmes.

(e) *Basin irrigation improvements* such as:

1. Adopting higher discharges, reduced widths or shorter lengths to permit a fast advance time, improved uniformity of infiltrated depths along the field, higher DU and AE, which makes it possible to reduce the volumes applied and an easier control of the leaching fraction. These improvements are easy to adopt but have limitations due to field size and geometry.
2. Corrugated basin irrigation for row crops, i.e. a system of furrows and beds installed inside the basin. These furrows favour a faster advance while cultivation of the beds improves the emergence and rooting of the crops. Adopting corrugated basins for row crops makes it easier to attain higher DU and water savings. This practice is easy to implement in both modern and traditional systems.

(f) *Paddy rice irrigation*

1. Replacing permanent basin flooding by temporary, intermittent flooding where the soil water is maintained near saturation for most of the time. These conditions decrease seepage, deep percolation and evaporation losses, and create conditions that favour storing any storm rainfall. However, this practice is limited to regions having warm to hot climates where the water is not playing a role for temperature regulation. It cannot be practiced in areas where deliveries are not frequent enough to keep the soil water above the critical threshold.
2. Where permanent flooding is practiced, water savings may be achieved by maintaining low water depths in the rice paddies because seepage and percolation losses are then controlled, and better conditions occur to store any storm rainfall if the basin bunds are high enough. Low flooding levels require appropriate land levelling.

TABLE 8.13. Improvements in surface irrigation systems aimed at reducing volumes applied and increasing the water productivity to cope with water scarcity

Techniques	Benefits	Applicability
Land levelling (precision levelling)	▪ Less water to complete advance, better conditions for adopting deficit irrigation and control of the leaching fraction	▪ Requires support to small farmers
Irrigation with anticipated cut-off	▪ Reduced water application, runoff is avoided and percolation is minimal	▪ Easy to apply when available water is limited
Basin irrigation		
▪ Higher discharges, reduced widths and/or shorter lengths	▪ Fast advance time, reduced volumes applied, easier application of deficit irrigation and control of the leaching fraction	▪ Easy; limitations are due to field size and geometry
▪ Higher basin dikes to catch storm rainfall	▪ Providing for full conjunctive use of irrigation and rainfall	▪ Easy to implement, mainly for paddy fields
▪ Corrugated basin irrigation for row crops	▪ Faster advance, improved emergence and rooting of the crops planted on the bed, easy introduction of row crops in rotation with rice	▪ Easy to implement
▪ Maintaining low water depths in rice basins	▪ Lower seepage and percolation losses and better conditions to store any storm rainfall	▪ Limitations when land levelling is poor and delivery is infrequent
▪ Non-flooded paddies, i.e. maintaining the soil water near saturation	▪ Lower seepage, deep percolation and evaporation losses, and better conditions to store any storm rainfall	▪ Only for paddies in warm climates and when deliveries are frequent
Furrows and borders		
▪ Irrigation with alternate furrows	▪ Reduced water application to the entire field and deep rooting of the crops is favoured	▪ Easy to apply
▪ Reuse of tail water runoff	▪ Avoidance of runoff losses, increased systems efficiency and control of quality of return flows	▪ Need for collective facilities in small farms
▪ Closed furrows and borders	▪ Avoiding runoff at the downstream end	▪ Easy (in flat lands)
▪ Contour furrows	▪ Runoff and erosion control in sloping land	▪ When fields are not oriented down slope
▪ Surge flow	▪ Faster advance, reduced percolation and runoff losses, higher performance and provides for system automation	▪ Easy for large farms but difficult for small ones
▪ Continuously decreased inflow rates, (cablegation)	▪ Control of percolation and runoff losses by continuously adjusting flow rates to infiltration, and provides for system automation	▪ Requires technological support and is difficult for small farmers
▪ Improved furrow bed forms	▪ Improved furrow hydraulics and infiltration that favour other improvements for water saving	▪ Requires appropriate implements; large farms
On-farm water distribution		
▪ Gated pipes and layflat pipes	▪ Easier control of discharges, control of seepage and provides for automation	▪ Easy to adopt but require farmers investment
▪ Buried pipes for basins and borders	▪ Easier control of discharges, control of seepage and easy to be automated	▪ Less appropriate for small farms
▪ Lined on-farm distribution canals	▪ Easier control of discharges when siphons and gates are used, and control of seepage losses	▪ Only for large farms
▪ Good construction of on-farm earth canals	▪ Easier control of discharges when using siphons and some control of seepage losses	▪ Limitations due to farm implements available
▪ Automation and remote control of farm systems	▪ Improved conditions for operation, easier application of improved irrigation scheduling, including in real time, and precise irrigation management techniques	▪ Application only to large farms with high technological and financial capabilities

3. Adopting basin dikes high enough to catch storm rainfall provides for full conjunctive use of irrigation and rainfall, which can generate important water conservation if the season irrigation coincides with a period when rain storms occur.

(g) *Improvements in furrow and border irrigation,* including*:*

1. Irrigation with alternate furrows (mainly during vegetative crop stages) to reduce water application to the entire field and favouring deep rooting of the crops. In cases of limited water availability and/or water stress resistant crops, this technique may be applied for the entire crop season.
2. Closed furrows and borders to avoid tail end runoff. However, in the case of very flat land, waterlogging at the downstream end may result if excess water is applied.
3. Reuse of tail water runoff, which is the only way to make efficient use of water where tailwater runoff occurs, i.e. open furrows and borders. Reuse increases system efficiency, preserves the quality of the downstream water bodies by avoiding runoff from the field system and provides for water saving that may be as high as 40 % of the applied volumes. It is easy to adopt in large farms but collective reuse facilities are generally required for small farms.
4. Contour furrows, to be adopted when land has a gentle slope and where down slope furrows would produce high runoff and erosion. However, it is not applicable when fields are narrow and down slope oriented.
5. Surge flow, i.e. intermittent, cycling of water application to furrows and, less frequently, to borders. Surging produces changes in the soil surface conditions that provide for a faster advance in moderate to high infiltration soils and for reduced percolation and runoff losses. Higher DU and AE are attained. Since surging requires control on the cycles times, it usually requires system automation. It is easy to apply in large and commercial farms but it is difficult for small farms.
6. Application of decreasing inflow rates to furrows to progressively adjust the flow rates to the diminishing soil infiltration rates, namely adopting the automated cablegation system. This technique controls percolation and runoff losses, produces higher DU and AE, and may lead to reasonable water savings. It requires an automation system. However, the application of this technique requires technological support and it is difficult for small farmers.
7. Improved furrow and bed forms, which improve the water flow conditions in the furrows together with infiltration conditions. However, it requires appropriate implements and is difficult to apply. Impacts on water saving are limited.

(h) *Water efficient systems to deliver water to basins, furrows and borders:*

1. Gated pipes and layflat pipes to convey and deliver the water to basins, furrows and borders. This equipment, relative to traditional earth canals or ditches, provides easier control of discharges applied to furrows, borders and basins, reduces seepage losses, and is easy to automate, especially for surge flow and cablegation referred to above. Gated pipes and layflat tubes are easy to adopt, even by small farmers.
2. Buried pipes for delivering water to basins and borders also provide easy control of applied discharges, reduced seepage and avoid runoff losses. They are easy to automate but require higher investments than gated pipes or improved farm irrigation ditches.
3. Lined on-farm distribution canals, which permit good control of discharges applied to furrows when siphons are used, and to borders and basins through gates or valves.

Lining controls seepage losses. Limitations in use are caused by investment costs and disturbance of other farming operations because these structures are permanent, as opposed to gated pipes that are movable.

4. Improved on-farm earth ditches and canals are an alternative to lining and also improve control of discharges distributed to furrows, basins and borders. However, resulting reductions in seepage losses are small and they require special farm implements for their reconstruction every year, which is unrealistic for small farmers.
5. Automation and remote control of farm systems improve conditions for the farm system operation, mainly to apply improved irrigation scheduling, including in real time, and precise irrigation management techniques. However, these technologies can only be adopted by large farms which have high technological and financial capabilities.

Some of the listed improvements are of general application. However, they are important for water conservation and saving in water scarce areas. Others are specific for situations when there are restrictions in water supply volumes. Improvements not directly related to water scarcity are based upon attaining higher distribution uniformity. The importance of high DU for achieving higher yields and using less water in surface irrigation is well evidenced in the literature.

A main factor for achieving high DU is land levelling. An example for water saving refer to a study on winter wheat irrigation in the North China Plain, where water for irrigation is becoming increasingly scarce and the groundwater level is now often below sea level. Results show that when land levelling was improved in long basins having an inverted slope near the downstream end, appreciable water savings could be achieved. These are close to 320 mm when the actual inflow rate per unit width is small (2.5 l/s/m) and near 180 mm when a larger inflow rate (4.5 l/s/m) is available (Li and Calejo, 1998). When comparing these figures with the irrigation requirement for wheat, which varies from 280 to 450 mm (dry year), one can understand the importance of implementing water saving practices. Sousa *et al*. (1995) have shown that enhancing DU from 65 to 83% leads to a yield increase of 8% for level basin irrigated maize, while improving DU from 44 to 76% produced a yield increase of 22%. For these situations the reduction in demand is 160 and 390 mm, respectively. The role of precision levelling in level basin irrigation was recently analysed for Egypt (Clemmens *et al.,* 1999). When high DU is achieved, deep percolation is better controlled, and the leaching fraction required for irrigation in saline soils, which is frequent in arid and semi-arid regions, is reduced.

Surface irrigation systems are, in general, not able to apply small irrigation depths but only large ones. Because of system and delivery scheduling constraints, irrigation scheduling has to be simple. The use of easy irrigation calendars, or the adoption of scheduling charts produced by irrigation scheduling simulation models to take into consideration the actual climatic demand, are in general useful. An example of an improved irrigation schedule for winter wheat in the North China Plain (Table 8.14) shows that the demand can be reduced by about 1/3 of the presently applied totals, i.e. near 200 mm, when both the irrigation system and the irrigation schedules are improved.

TABLE 8.14. Comparison of current and optimal irrigation depths for winter wheat in Xiongxian, North China Plain, for different climatic demand probabilities (adapted from Fernando *et al*., 1998)

Irrigation dates	Actual irrigation depths (mm)		Irrigation depths under system constraint (mm)		Target irrigation depths (mm)		
	Observed range	Observed average	More favourable slope	Less favourable slope	average	dry year	very dry year
At planting	90-230	156	70	75	-	70	70
Winter	116–142	129	105	115	90	90	90
Spring	116–140	124	100	110	80	80	80
At heading	119-143	133	80	85	80	80	90
At filling	84-117	97	70	75	80	90	100
Total		640	425	460	330	410	430
Demand reduction			215	180	155	230	210

8.8.3. Demand management: improving sprinkler irrigation systems

Main sprinkler systems are:

- *Set systems*: the sprinklers irrigate in a fixed position and can apply small to large water depths. Set systems include solid set or permanent systems as well as periodic-move systems, which are moved between irrigations, such as hand-move, wheel line laterals and hose-fed sprinklers. These systems are the least costly and the best adapted for small farms. A wide range of sprinklers can be selected for a variety of crops and soils as well as for environmental conditions.
- *Travelling guns*: a high pressure sprinkler continuously travels when irrigating a rectangular field. The high application rates and the characteristics of the moving system make travelling guns unsuitable for applying very small or large depths, or to irrigate heavy soils and sensitive crops. In addition, these systems have a high energy requirement and may have low performances and high evaporation losses when operating under hot, arid and windy conditions.
- *Continuous move laterals*: the sprinklers operate while the lateral is moving in either a circular or a straight path. Large laterals are used, equipped with sprinklers or sprayers. The principal continuous-move systems are center-pivot and linear move laterals These systems are designed to apply small and frequent irrigation in very large fields.

In sprinkler irrigation, the irrigation uniformity essentially depends upon variables characterising the system such as the pressure, discharge, throw and application rate of the sprinklers, spacing between sprinklers and between the pipe laterals where sprinklers are mounted, and head losses along the pipe system network. These variables are set at the design phase and they are difficult to modify by the farmer. Thus DU is the performance indicator that characterise the irrigation system. The efficiency AE depends upon the same system variables as DU, and on management variables concerning system maintenance and, moreover, the duration and the frequency of the irrigation events. The AE indicator often follows DU and largely depends upon the irrigation scheduling applied. Thus, the irrigator can do little to improve the uniformity of irrigation and is constrained by the system characteristics for any improvements in irrigation performance (Pereira *et al.*, 2002).

Field evaluations can provide good information to farmers on how to improve

management and introduce limited changes in the system, as well as useful feedback to designers and to those who manage quality control of design and services. Field evaluations allow the identification of problems in sprinkler systems under operation. In set sprinklers, the uniformity is often lower than that potentially attainable due to (i) excessive spacings between sprinklers and laterals, (ii) too much variation in pressure within the operating system, and (iii) insufficient or excessive pressure at the sprinklers. The main problems in travelling guns refer to (i) excessive distance between towpaths, (ii) inadequate pressure, (iii) asymmetric wet angle, and (iv) variable advance velocity. In lateral moving systems, more frequent causes for non-uniformity are (i) inadequate pressure distribution along the lateral, mainly when operating in non flat areas, (ii) application rates much above infiltration rates, (iii) use of a end gun sprinkler without an appropriate source of pressure, and (iv) excessive pressure in systems with sprayers. Wind effects are common to all systems but are more often a problem in travelling gun and lateral moving systems. Problems reported above are generally due to poor design, or lack of design, where solutions are found exclusively to lower the investment costs. In addition, very often, the farmers have a very poor knowledge of their own systems and do not receive extension support for system selection or to maintain and manage the systems.

As for surface irrigation systems, the distribution uniformity plays a major role in sprinkler irrigation and is the main factor influencing system performances. The lower the DU, the larger is the difference between applied depths in the over-irrigated and the under-irrigated parts of the field, and thus the larger is the depth of water required to satisfy a given target application in the entire field. Consequently, the water use increases when DU decreases. As observed by Mantovani *et al.* (1995), when DU is low (40 %) the farmers use nearly twice as much water as is applied when the DU is high (85 %). However, if water is expensive farmers under-irrigate for low system uniformity and only fully irrigate when systems can achieve a high DU. Therefore, when looking for improvements of sprinkler systems to cope with water scarcity the most important factor to be considered is to attain higher distribution uniformity. This is in agreement with the trend to adopt a target DU for design (Keller and Bliesner, 1990, Seginer, 1987) and to use DU as the main constraint in the optimisation of crop patterns (Tarjuelo *et al.*, 1996).

The improvement of sprinkler irrigation systems to cope with water scarcity, as summarised in Table 8.15, mainly concerns a variety of practices aimed at reducing the volumes of water applied, particularly to increase DU and AE, and to increase water productivity. These practices and measures refer to:

(a) *Optimising the overlapping of sprinkler jets,* through:

1. Adopting sprinkler spacings in agreement with the characteristics of the sprinklers relative to the wetted diameter, which is influenced by the available pressure. The aim is to attain adequate distribution uniformity which will enhance the economic return of the crop.
2. Similarly, choose the appropriate distance between travelling gun towpaths.
3. Based in results of field evaluations of operating systems, in the case of movable set systems, adjust the position of laterals when they are moved and, for travelling guns, adjust the towpath spacings in accordance with the conditions observed in field on the day.

TABLE 8.15. Improvements in sprinkler irrigation systems aimed at reducing volumes of water applied and increasing water productivity to cope with water scarcity

Techniques	Objectives/Benefits	Applicability
▪ Adopt or correct sprinkler spacings for high DU in set systems	▪ *Optimising overlapping of sprinkler jets*	▪ Easy at design, difficult once installed
▪ Adopt or correct towpath spacings for travelling guns		▪ Easy at design, possible when operating
▪ Change sprinkler nozzles to suit available pressure		▪ Relatively easy and not expensive
▪ Enhanced alignment of continuous lateral move systems		▪ Higher investment cost
▪ Design for pressure variations not to exceed 20 % of the average sprinkler pressure	▪ *Minimising discharge variations within the operation system*	▪ Easy to set at design
▪ Pressure regulators in sloping fields		▪ Easy at design and after installation
▪ Booster pumps for end gun sprinklers in moving laterals		▪ Easy at design and after installation
▪ Monitor and adjust pumping equipment		▪ Needs technical support
▪ Irrigation during non windy periods	▪ *Minimising evaporation and wind drift losses*	▪ Limitations when delivery is rigid
▪ Smaller spacings in windy areas		▪ Easy to set at design
▪ Sprinklers with low jet angles for windy areas		▪ Easy to set at design
▪ Suspended spray heads or LEPA piping and heads instead of sprinklers on the top of laterals		▪ Easy to set at design; costly after installation
▪ Large sprinkler drops and application rates in windy areas		▪ Constrained by crops and soil infiltration
▪ Orient set laterals and travelling gun towpaths perpendicular to prevailing wind direction		▪ Constrained by the design options
▪ Avoid gun sprinklers under high winds and heavy soils		▪ Design decisions
▪ Adopt application rates smaller than infiltration rate	▪ *Maximising infiltration and avoid runoff losses*	▪ Easy for set and travelling gun systems
▪ Soil management practices that favour infiltration		▪ Need technical support and investment
▪ Furrow dams in sprinkled sloping fields (row crops)		▪ Easy for contour corrugated fields
▪ Adapt speed and cycles of mobile systems to soil infiltration rates		▪ Limitations due to design and soil conditions
▪ Improved spray heads and booms in lateral move systems on heavy soils and sloping land		▪ Higher investment cost
▪ Careful maintenance	▪ *Pre-condition for higher performances*	▪ Easy to implement
▪ Automation and remote control, and precise water application	▪ *Enhanced conditions to adopt advanced irrigation and energy management strategies*	▪ Only for large farms having advanced technological standards
▪ Adopt fertigation (fertilisers in water)	▪ *Improves fertiliser and water use efficiency*	▪ Easy but requires advice and investment

4. Also based on field evaluations, change sprinkler nozzles to make best use of the available pressure to improve overlapping.
5. Adopt adequate alignment tools in continuous-move lateral systems to increase uniformity of water application.

(b) *Minimising discharge variations within the operation system*

1. Design set systems to avoid excessive pipe head losses and control pressure variations to no more than 20 % of the average pressure at the sprinklers, so as to attain appropriate uniformity.
2. Adopt pressure regulators in sloping fields to avoid non-uniform discharges and runoff where excess pressure would produce excessive application rates. This measure can be adopted in operating systems when field evaluation reveals the corresponding problems.
3. Adopt pressure regulators in continuous-move lateral systems that operate in sloping fields and booster pumps when an end gun sprinkler is used.
4. Monitor and adjust the pumping equipment to ensure the upstream pressure matches that required by the sprinkler system. This ensures conditions suitable for optimal functioning of the system to attain higher DU. This measure requires appropriate technical support for farmers.

(c) *Minimising wind drift and evaporation water losses by*:

1. Avoiding irrigating during windy periods of the day and the hours when evaporation is high. However, this practice is constrained by system characteristics and by water delivery rules when a rigid rotation is applied.
2. Use smaller spacings in windy areas to compensate for the jet disturbance caused by the wind. This option is easy to implement in new systems but requires higher investment costs.
3. Select sprinklers with the lowest possible jet angles for windy areas.
4. In case of continuous-move lateral systems, use suspended spray heads instead of sprinklers mounted on the top of the lateral, or adopt the LEPA suspended emitter heads to minimise the wind effects. However, because drop heads have higher application rates, special care is required to prevent this type of solution producing excessive runoff (and erosion).
5. Adopt sprinkler pressures that produce large drops and sprinklers having high discharge rates in windy areas. However, these options are limited by the sensitivity of crops and the soil infiltration characteristics.
6. Orient set laterals and travelling gun towpaths perpendicular to wind to compensate for the jet disturbance.
7. Avoid gun sprinklers under high winds and in heavy soils because under these conditions wind drift and runoff losses are unavoidable.

(d) *Maximise infiltration of applied water and avoid runoff losses:*

1. In set and travelling gun systems, design systems for sprinkler application rates not exceeding the soil infiltration rate to avoid the runoff and erosion,
2. For heavy soils and sloping lands, where infiltration is lower, adopt soil management practices that favour infiltration as described in section 8.7.4.
3. Adapt speed and cycles of continuous-move laterals to soil infiltration rates, i.e.

minimise the time duration of water application in excess of infiltration rates. Extension support is generally required, in addition to good design.

4. Where relatively high sprinkler application rates are used, adopt furrow dams in sloping fields for row crops to store the non-infiltrated water in the ponds thus created and, therefore, avoid runoff. This practice, despite being costly, is highly effective in contour corrugated fields when slopes are not very high, but it is of limited benefit when cultivation is practised down slope and/or slopes are quite steep.
5. In continuous-move lateral systems, use improved spray heads and sprayers on booms when irrigating low infiltration soils, particularly in undulating fields, to reduce the application rates and to control runoff and erosion. These design issues are more costly than the use of more common solutions but they are very effective in controlling the application rates.

(e) *Adopt careful system maintenance* since it is a pre-condition for adequate functioning of the equipment and to achieve higher performances.

Other less specific measures contribute to improving the water use in sprinkler systems. However, most of the related technologies apply only to large commercial farms having high technological support. This is the case for automation and remote control, which support enhanced management, including precise water application, real time irrigation scheduling and energy management strategies. It is also the case for fertigation - the application of fertilisers with the irrigation water – that improves the use of both the water and the fertilisers, and precise water application - when advanced information systems make it possible to apply differentiated water and fertiliser amounts allowing for differences in soil conditions and crop development.

Sprinkler system design is another area of concern because, as reported above, water savings are often hampered by poor design. New approaches are required not only to enhance design procedures but also to adopt specific approaches relative to design for management under scarcity. Then, mainly using models and expert systems tools, sprinklers and systems layout could be selected and simulated in response to specific environmental conditions and target performances. Field evaluation then plays then a major role because, in addition to farmers advice, it produces relevant factual information that can be used in design.

8.8.4. Demand management: microirrigation systems

Microirrigation, also called trickle or drip irrigation, applies water to individual plants or small groups of plants. Application rates are usually low to avoid water ponding and minimise the size of distribution tubing. The microirrigation systems in common use today can be classified in two general categories:

- *Drip irrigation,* where water is slowly applied through small emitter openings from plastic tubing. Drip tubing and emitters may be laid on the soil surface, buried, or suspended from trellises.
- *Microspray irrigation,* also known as *micro-sprinkling*, where water is sprayed over the soil surface. Microspray systems are mainly used for widely spaced plants such as fruit trees but in many places of the world they are used for closed space crops in small plots.

A third type of localised irrigation, the bubbler systems, use small pipes and tubing to deliver a small stream of water to flood small basins adjacent to individual trees. Bubbler systems may be pressurised with flow emitters, or may operate under gravity pressure without

emitters

Microirrigation uniformity depends upon various system variables such as pressure variation and emitter discharge variation, emitter flow characteristics (pressure – discharge relationship, susceptibility to variations in temperature, emitter orifice size in relation to susceptibility to clogging), emitter material and manufacturing variability, emitter spacings, head losses in the lateral tubing, pressure variation due to field slopes, and filtering characteristics. With the exception of maintenance, the farmer can do very little to achieve good distribution uniformity. As for sprinkler systems, DU is the indicator for the system performance and essentially depends on decisions taken at design. The application efficiency mainly depends upon the same system variables as DU and on management variables related to the irrigation frequency and time duration. Therefore, the farmer may improve the application efficiency when adopting appropriate irrigation schedules, but performances are limited by the system constraints.

Field evaluations also play an important role in guiding farmers, creating information for design of new systems, and for quality control of design and services. Results of field evaluation show that micro-irrigation performances are often lower then expected. Pitts *et al*. (1996), referring to the evaluation of 174 micro-irrigation systems in USA, found an average DU of 70%, with seventy-five percent of cases having DU below 85%. DU values lower than the target are observed world-wide. Low DU is mainly due to inappropriate control of pressure, discharge variation within the operating set, insufficient filtration and filters maintenance, lack of pressure regulators, poor selection of emitters, and poor information on manufacturing specifications and characteristics.

Uniformity in micro-irrigation affects the water saving capabilities of the systems, crop yields, and water productivity. For a long time it has been known that micro-irrigation design should base upon uniformity (Bralts *et al*., 1987). Santos (1996) shows that tomato yields fall from near 102 ton/ha to 85 ton/ha when uniformity drops from 90% to only 60%. In the first case the yield was achieved with 470 mm of applied water while water use increased to 500 mm when uniformity was only 60%. This data agree with those referred to above for sprinkling but the increase in water use with conventional sprinkling is less dramatic. An extensive analysis by Ayars *et al*. (1999) shows the benefits for several crops of subsurface drip. It can serve to maximise yields and considerably reduce water demand relatively to other methods.

Improvements in micro-irrigation systems to cope with water scarcity aim at achieving high uniformities of water distribution (DU) in the entire field. This is seen as a pre-condition for efficient water use and productivity as well as to achieve water savings. They are summarised in Table 8.16 and concern:

(a) *Use of a single drip line for a double crop row* to reduce water use (and system costs) when the soil has enough good lateral transmission of water to wet both rows.

(b) *Use microsprayers in high infiltration soils* to avoid deep percolation losses that would be produced by drippers. It is easy to apply in orchards and low crops but not for tall crops. Then sprinkling would be more appropriate.

(c) *Adjust the duration of water application and timing to soil and crop characteristics* to control percolation losses and salt distribution and accumulation in the soil. For difficult conditions, support by extension services may be required.

TABLE 8.16. Improvements in micro-irrigation systems aimed at reducing volumes of water applied and increasing the water productivity to cope with water scarcity

Techniques	Benefits	Applicability
▪ Single drip line for a double crop row	▪ Reduced water use	▪ For soils having good horizontal conductivity
▪ Microsprayers in high infiltration soils	▪ Avoid deep percolation losses which would be produced by drippers	▪ Orchards and low field crops
▪ Use drippers in low infiltration sloping soils	▪ Avoid runoff losses which could be produced by microsprayers	▪ No limitations
▪ Adjust application duration and timing to soils and crops	▪ Control of percolation losses and salt distribution and accumulation in the soil	▪ May require support of extension services
▪ Adopt pressure regulators in large sets and in sloping areas	▪ Provide for emitter uniformity by avoiding variations in pressure in the operating set	▪ To be implemented at the design stage
▪ Adopt self-compensating emitters in long and sloping laterals	▪ Provide for emitter uniformity by avoiding variations in pressure along each lateral	▪ Design limitations
▪ Use appropriate filtering and filters locations	▪ Control emitter clogging and consequent non-uniformity of emitter discharges	▪ To be defined at the design stage
▪ Frequent filter cleaning	▪ Control of emitter clogging	▪ Depends on the water quality
▪ Chemical treatment to combat emitter clogging	▪ Helps appropriate functioning of emitters	▪ To be implement out of crop season
▪ Careful maintenance	▪ Pre-condition to fully use the beneficial characteristics of the system	▪ According to system characteristics
▪ Automation	▪ Helps operation and the adoption of irrigation scheduling, mainly in real time	▪ Requires advice and investment
▪ Adopt fertigation (fertilisers with the irrigation water)	▪ Enhances water and fertiliser efficiency	▪ Requires advice/expertise
▪ Adopt chemigation	▪ Easy control of weeds and soil diseases	▪ Requires advice/expertise
▪ Improve system design for management under scarcity	▪ Provides for selecting emitters and system layout in agreement with environmental conditions, and helps to adopt non-optimal operation under conditions of limited water supply	▪ Requires technical support to farmers
▪ Field evaluation	▪ Identification of corrective measures to the system and, mainly to its management and maintenance	▪ Requires appropriate monitoring and extension services

(d) *Control pressure and discharge variations within the operating set*:

1. Adopt pressure regulators in sloping areas to avoid pressure variations due to slope. Because micro-irrigation systems operate at quite low pressure, variations in elevation induce changes in pressure that are relatively high when compared with sprinkler systems. Pressure regulators may be installed in operating sets when these problems are identified through field evaluation.
2. Adopt self-compensating emitters in long and/or sloping laterals. This is an alternative to some cases where pressure regulators may be less efficient. Changing from turbulent emitters to self-compensating emitters following an evaluation is generally not feasible since it implies heavy costs.

(e) *Use filters appropriate to the water quality and the emitter characteristics,* implying:

1. Selection of equipment and filtering sizes adequate to the problems to be solved, which is often more expensive than common equipment.
2. Select filter locations in agreement with the system layout and the management adopted for the sub-sets, including fertigation management.
3. Adopt carefully maintenance of the filters since they produce quite heavy head losses when they are not cleaned with appropriate frequency.
4. Apply chemicals periodically to clean the system and treat the clogged emitters.

(f) *Adopt careful maintenance* since it is essential for achieving high performance.

(g) *Adopt automation.* Micro-irrigation systems apply water with very high frequency and the systems are often divided in several independent sets. Ease of operation requires that automation be used for appropriate implementation of irrigation and fertiliser management.

(h) *Adopt fertigation and chemigation* – i.e. application of fertilisers and herbicides or other soil chemicals with the irrigation water. These usually improve water use and plant responses to irrigation and fertiliser/chemical treatments.

The discussion above essentially refers to the need for good design and management when micro-irrigation systems are used in water scarce areas. Since these systems apply water only in a part of the field and near the crop roots, they are able to provide for higher production using less water than other irrigation systems, i.e. adopting micro-irrigation systems is a way to cope with water scarcity. However, these systems are much more expensive than surface and sprinkler systems despite the fact that costs tend to become lower over time. This implies that their adoption has to be economically feasible or, in other words, that yields must be high enough to produce high farm incomes. To achieve this, systems have to be designed for achieving the best results without system water losses, but they cannot be designed just to save water. However, progress in design are required to find solutions that may allow the systems to operate under optimal and non-optimal conditions when water is not sufficient to fully satisfy the crop requirements. In addition, as for other systems, field evaluation of operating systems are also required to provide information to farmers to improve their systems and to produce information that may be useful for design, including obtaining the best possible results under non-optimal conditions when water is not sufficient.

8.8.5. Demand management: irrigation scheduling

8.8.5.1. Irrigation scheduling techniques

Research has provided a large variety of tools to support improved irrigation scheduling, i.e. the timeliness of irrigation and the adequateness of volumes applied.

Irrigation scheduling techniques may be used with diverse objectives in the practice of farmers. More commonly, farmers seek to avoid any crop stress and maximise crop yields. When water is plenty, farmers tend to over-irrigate, both anticipating the timing of a need for irrigation and applying excessive water depths. Thus, the application of appropriate irrigation scheduling techniques permits them to optimise the timeliness and the volumes applied, thus controlling return flows, deep percolation, transport of fertilisers and agro-chemicals out of the root zone, and avoiding waterlogging in the parts of the field receiving excess water. Economic and environmental benefits are also obtained because better conditions are created

for achieving the target yields, less water is used, the contamination of surface and groundwaters is controlled, the rising of saline water tables is avoided and, when the water source is the groundwater, the respective water levels are easily kept in the desirable depth range. In water scarce regions, achieving such optimal management conditions is more important then under conditions of plenty since any excess in water use is a potential cause for deficit for other users or uses. Since water availability is usually limited, and certainly insufficient to achieve maximum yields, some kind of reduced demand scheduling has to be used.

Reduced demand scheduling may be managed under very well controlled approaches as for deficit irrigation, or just to minimise the effects of water stress as for reduced irrigation when drought occurs. *Deficit irrigation* is an optimising strategy under which crops are deliberately allowed to sustain some degree of water deficit and yield reduction. *Reduced irrigation* is a remedial strategy where crops are irrigated using the minimal amounts of water available during the more critical growth periods in such a way that some yield may be achieved and, for perennial crops, future yields are not compromised. Therefore, for deficit irrigation the timeliness and volumes of water applied must be well scheduled in such a way that the economic returns of the irrigated crops are optimised. On the other hand, for reduced irrigation only the water productivity may be optimal, but decisions do not follow any optimisation process: farmers just try to crop and achieve the best possible yield by selecting the timings when the limited water resources are applied (e.g. in subsistence cropping). Deficit irrigation is a sustainable strategy that should include in selected irrigation events the volumes required for leaching if poor quality water is used or when irrigating saline soils. Alternatively reduced irrigation is not sustainable since yields do not respect any economic threshold and leaching requirements are not considered. In the long term, subsistence farming and increased soil salinity do not assist in maximising the yield and economic productivity of the water and controlling the impacts of irrigation on the environment.

However, deficit irrigation under saline conditions is difficult, particularly in arid conditions. To make deficit irrigation and salinity control compatible may not be achievable. Then, reduced demand takes the form of *controlled saline irrigation* where leaching is achieved regularly through most seasons but not in years when water is scarce. Provisions for additional leaching have to be made as soon as more water is available. Several procedures may be used as outlined in Section 7.3.4.

Irrigation scheduling techniques and tools are quite varied and have different characteristics relative to their applicability and effectiveness for coping with water scarcity. Many of them are still only applicable in research or need further developments before they can be used in practice. Most of them require technical support by extension officers, extension programmes and/or the technological expertise of the farmers. However, there is great potential for their application in practice when appropriate programmes are implemented at regional or project level, namely oriented for effective support to small farmers. The problem is that in most countries these programmes do not exist because they are expensive, trained extension officers are lacking, there is not enough awareness of the issues of water saving in irrigation or the institutional mechanisms developed for irrigation systems management give low priority to the farm systems. Therefore, in general, large limitations occur for their use in the farmers practice.

The irrigation scheduling techniques, summarised in Table 8.17 with reference to the respective applicability and effectiveness, may be grouped as follows.

(a) Techniques and tools using *soil water indicators*. They correspond to different levels of accuracy and sophistication, and all are useful to support diversified programmes to advise farmers on the most adequate irrigation scheduling to be practised. The accuracy of information relates to the sampling methods adopted and to the selection of locations where point observations are performed due to the soil water variability both in space and in depth. The following techniques are used:

1. *Soil appearance and feel*, which is the simplest approach used by many farmers, consisting of assessing the soil water status by just feeling how dry the soil is. It can be quite effective to assess the timeliness of irrigation when the farmers, using a simple shovel or a hand probe, perform observations in the entire root zone and not only on the soil surface. The farmers need to have some experience in sensing changes in the soil moisture by hand touching the soil. However, it is not possible to assess the amount of water required, and thus constant irrigation depths are used, which are estimated according to the irrigation method adopted.
2. Assessing the soil water content by *sensing changes in the electrical resistance of the soil* due to variations in soil moisture. This is performed using porous blocks and electrode probes, which are easy to use but require calibration when more precise readings are required. This technique is generally applicable in cash crops since it implies costs of equipment and requires advice from extension officers. Its effectiveness to cope with water scarcity depends upon how crop specific irrigation thresholds are selected and used.
3. *Measurement of the soil water potential* with tensiometers, soil psychrometers and pressure transducers, all of which are highly precise instruments. These can be used easily with tree and horticultural crops but require expertise and external support to define the irrigation thresholds. They are highly effective for defining the timeliness of irrigation and are easy to use when irrigation depths are constant throughout the irrigation season. However, the sensors are difficult to use if the soil is allowed to dry more than usual, beyond the range of the sensing ability of equipment.
4. *Measurement of the soil water content* through soil sampling for laboratory analysis, or using neutron probes or TDR (time-domain reflectometry). These techniques are very precise, their applicability is very large, and they are extremely helpful to support any water balance technique in real time. Data provides information for precisely determining the irrigation timing and depths when irrigation thresholds are well established. However, these tools are expensive and their use requires expertise and/or external support to farmers.
5. *Measurement of the soil water content and potential*, which is a more sophisticated approach since it combines two of the types of measurements referred to above, generally neutron probe or TDR measurements and tensiometers. It is only applicable in highly advanced technological farms and in research and experimentation.
6. *Remotely sensed soil moisture* is a technique that still is out of the reach of farmers practice because the information provided is generally poor for deeper soil layers. Observations are performed with an airborne thermal infrared scanner and spatially distributed data refers to large areas. Further development is required.

TABLE 8.17. Irrigation scheduling techniques, tools, applicability, and effectiveness to cope with water scarcity

Irrigation scheduling techniques	Tools/procedures	Applicability	Effectiveness
Soil water indicators			
Soil appearance and feel	Hand probe, shovel	Field crops	Depending on farmers experience
Soil electrical resistance as depending on soil water content	Porous blocks, and electrode probes	Cash crops; calibration and advice are desirable	Depending upon selected irrigation thresholds
Soil water potential	Tensiometers, soil psychrometers, pressure transducers	Tree crops and horticultural crops. Calibration and advice to farmers are desirable	Very high when thresholds are well selected. Not appropriate for low irrigation thresholds
Soil water content	Soil sampling, neutron probe, and TDR (time-domain reflectometry)	All crops. Requires support by experts	Very high when thresholds are well selected
Soil water content and potential	Neutron probe or TDR and tensiometers	Research	Very high
Remotely sensed soil moisture	Thermal infrared scanner	Large areas	Limited
Crop indicators			
Appearance and feel	Observation of plant (leaf) signs of stress	Crops that give sign of stress prior to wilting	Depending on farmers experience
Leaf water content	Sampling	Research	Limited
Leaf water potential	Pressure chamber, psychrometers	Research	Very high
Stomatal resistance	Porometer	Research	High
Canopy temperature (and crop water stress index)	Infrared thermometers	Field crops in large fields. Requires expertise and calibration	Very high when thresholds are well selected and for stable atmosphere
Changes in diameter of stems or fruits	Micrometric sensors	Tree crops. Requires expertise	Depending upon selected thresholds
Sap flow measurement	Electronic sensors	Mainly tree crops, yet at research stage	Very high when thresholds are well selected
Remote sensing of crop stress	Airborne and satellite scanners	Large cropped areas. Regional irrigation management programs	Not yet fully operative. Further progress is required
Climatic indicators			
Pan evaporation (together with rainfall data)	Evaporation pans and evaporimeters	Generally included in regional irrigation scheduling programs	High but depends on the way information is provided to farmers
Crop evapotranspiration (and rainfall)	Weather stations and crop coefficients	Generally included in regional irrigation scheduling programs	High but depends the way information is provided to farmers
ET measurements	Lysimeters, energy balance, etc.	Research	Very high
Remotely sensed ET	Thermal infrared and multi-spectral scanners and surface weather data	For regional irrigation management programs	Yet not fully operative. Further progress is required
Soil water balance			
Irrigation dates and depths to be applied	Water balance models using rainfall + ET, and crop and soil data	General application. Needs expertise, support by extension, or links with information systems	Very high but depend on farm technological development and/or support services

(b) Irrigation scheduling techniques using *crop indicators* are useful for assessing the timeliness of irrigation events but not for defining the irrigation depths. Therefore, crop stress indicators are useful when irrigation depths are predefined and kept constant during the irrigation season. Techniques include:

1. *Appearance and feel*, by observing any particular stress behaviour of the crop such as leaf rolling, leaf orientation, leaf colour, or by observing symptoms of water stress in more sensitive plants purposefully planted in selected locations of the cropped area for early warning of the crop stress. This technique is applicable to crops/plants that give detectable signs of water stress prior to wilting and its effectiveness depends upon the farmers skill in interpreting these signs.
2. The *leaf water content, leaf water potential and stomatal resistance* require relatively sophisticated equipment, timeliness for observations and expertise in interpretation of results. Thus, they are essentially used for research and not in farming practice or even by farmer advisers. However, data may be of very good quality and is particularly useful for research purposes.
3. Observations of the *canopy temperature* (and determination of the related crop water stress index) using hand held infrared thermometers (preferably together with observation of the vapour pressure deficit) are applicable to field crops in relatively large areas. This technique is based on the fact that the surface temperature of a well watered crop is some degrees lower than the air temperature while the surface temperature of a stressed crop is close to the air temperature. The applicability of this technique relates to the stability of the atmospheric conditions, which make it easy to compare canopy and air temperatures. Under conditions where air temperature changes often during the day due to cloudiness, the temperature difference between air and canopy also varies making it difficult to interpret the data. The use of this technique requires appropriate calibration of the water stress threshold, which is crop specific. Interpretation of data requires expertise and may be difficult when the cropped field is small. Farmer advisers often use this technique.
4. Observation of *changes in diameter of stems or fruits*, which are measured by using micrometric sensors. This technique is applicable to tree crops but requires expertise and well selected thresholds. Some commercial applications have been made available but their use in general farmer practice is limited.
5. *Measurement of sap flow* through plant stems is mostly applied to trees and other ligneous plants using appropriate electronic sensors. It is also useful in research to assess crop evapotranspiration. It requires expertise, well defined irrigation thresholds, and is difficult to use outside research and experimentation environments.
6. *Remote sensing of crop stress* uses airborne scanners sensing several wavelengths including the thermal infrared. It is applicable to large cropped areas but it is of difficult application when fields are small and there is a large variety of crops. It is useful to support irrigation programmes applied to large areas. Information may be made available through in a spatially distributed format with GIS (geographical information systems). Good expertise in interpreting and transmitting information to farmers are required. Further developments may be expected.

(c) The irrigation scheduling techniques using *climatic indicators* are widely used. They require local or regional weather data and some kind of water balance approach. The degree of accuracy depends upon the nature, quality and spatialisation of weather data, as well as the water balance approach used. Preferably, evaporation and

evapotranspiration data should be used as input of water balance computational tools or models, so not being used alone. Information may be processed in real time or, more often, using historical data. Techniques may be grouped as follows:

1. *Evaporation (Ev) measurements* with evaporation pans and evaporimeters or atmometers. This technique is applicable to every crop for estimating crop evapotranspiration (ETc) using appropriate coefficients that relate Ev to ETc. Pan evaporation data should be averaged to 7 or 10 days. Its effectiveness depends upon the reliability of Ev measurements, accuracy on computing ETc, and how data is handled to tell the farmers when and how much to irrigate. The easiest way is to just broadcast how much millimetres evaporation occurred in the past days. More useful is to inform, crop by crop, how much has been the ETc in a given "homogeneous" area.
2. *Assessment of crop evapotranspiration* using weather data from climatic stations to estimate the reference evapotranspiration (ETo) and crop coefficients to compute ETc from ETo (see Allen *et al.*, 1998). Direct ET measurements with lysimeters are only used for research. The effectiveness of this procedure depends upon the accuracy of data collection and calculation procedures, and on the approach used to provide information to farmers.
3. *Remote sensed ET* using thermal infrared and multi-spectral scanners combined with surface weather data. It is applicable to large areas but it is of limited value when fields are small and a large variety of crops exist. Preferably these data should be used with models and be available in a spatial format with GIS. It is useful for regional irrigation scheduling programmes.

(d) *Soil water balance* techniques, which estimate the crop irrigation requirements, are very useful for irrigation scheduling because they allow the determination of the irrigation dates and depths to be applied. Both real time and historical weather data (rainfall and ETc) may be used. Models may produce typical irrigation calendars with a relatively large time step calculation or daily calendars adjusted to the weather conditions prevailing. Soil water holding characteristics should be considered in addition to crop and climate data when performing the soil water balance to take into consideration the use of the stored water by the crop and, whenever possible, the capillary rise from the groundwater. Further sophistication in modelling includes the spatial distribution of data when operating the model in a GIS platform for supporting regional irrigation scheduling programmes. Technologically advanced farmers compute themselves the water balance when they have access to rainfall and ETc data and have support to describe soil and crop conditions. Alternatively, they may accede to a model through an assisted Web page. However, these cases are very infrequent and, for most cases, they may receive external assistance to use check books or other irrigation computational approaches when adhering to specific programmes for irrigation scheduling.

Irrigation scheduling, as described above, may be supported by a large variety of tools but can only be applied when the farmers have control on the timing and duration of irrigation. Under these conditions irrigation can be managed in relation to farmer targets. However, the full effectiveness of irrigation management can only be achieved when the farmer is able to control the timing and the depth or volume of the irrigation.

When surface irrigated areas are supplied from collective irrigation canal systems, farm irrigation scheduling depends upon the delivery schedule, e.g. discharge rate, duration of the

deliveries and frequency of supplies, which are dictated by the operational policies used for the conveyance and distribution system. Discharge and duration impose constraints to the volume of application, and frequency determines the timing of irrigation. Surface irrigation delivery systems are often rigid and the time interval between successive deliveries may be too long. Then, farmers apply all water that is made available and over-irrigation is often practised. Under these conditions the farmer adopts the irrigation scheduling that he is allowed by the system manager, i.e. the adoption of more rational irrigation scheduling and water saving practices depends upon the off-farm conveyance and distribution. Therefore, the improvement of the on-farm irrigation systems should go together with the modernisation of the delivery system to allow more flexibility in selecting the appropriate inflow rates and supply times.

Pressurised conveyance and distribution systems are often managed on demand, i.e. farmers are in control of irrigation timings and duration but, to certain limits imposed by economic and technical reasons, discharges available are limited. Therefore, irrigators supplied by these systems are free to select and adopt the irrigation schedules they consider more appropriate to their crops and farming practices. However, rigid delivery rules may be enforced by the system managers during periods of drought and limited water supply, which restrict farmers decisions. Then, farmers adapt irrigation timings and duration in accordance with the periods when water is delivered but they keep some degree of freedom to schedule irrigations. In alternative, when water is measured at the farm hydrants, system managers may impose restrictions on volumes and price penalties for excess water use. Then farmers have to optimise the respective schedules aiming at reducing the demand. Pressurised systems are therefore more favourable than surface systems for adopting rational irrigation scheduling practices, including when supply restrictions are imposed.

8.8.5.2. Reduced demand irrigation scheduling

Reduced demand irrigation scheduling implies the adoption of some irrigation scheduling technique, empirical or scientific. The information above, summarised in Table 8.17, may be helpful to understand how to select the irrigation scheduling tools in relation to crops, expertise required and limitations in use. In addition, there is the need to know how these techniques may be used to define the irrigation timings and depths, as summarised in Table 8.18 and described below. However, for better understanding it is appropriate to refer first to the constraints of the irrigation methods, which improvement issues are dealt in the precedent sections.

In surface irrigation, irrigation depths are generally large to very large, 80 to 120 mm, depending upon the system technologies applied in relation to the ability to apply target depths appropriate to the crop and the soil water reservoir. Larger values correspond to deep rooting crops in heavy soils. Smaller depths (30 to 50 mm) are only feasible when the field is precisely levelled and some degree of automation is used to control the volumes applied or when very small fields are irrigated by well experienced irrigators. In very permeable soils generally non-uniform and over-irrigation is practised, so surface irrigation should be avoided in these soils. Therefore, the rule is the adoption of large irrigation depths and low irrigation frequency, i.e. large time intervals between irrigations.

In sprinkler irrigation, depths depend upon the system. Set systems may apply very small depths (5 to 10 mm) with very high frequency when permanent and automated systems are available, up to large and infrequent irrigations when systems are movable. Generally

medium depths, around 30 to 40 mm with several days interval are common. Travelling rain-guns generally apply 20 to 40 mm at each event. Smaller and larger amounts are generally not feasible due to system constraints. Lateral moving systems are designed for small up to medium depths, 5 to 30 mm in general. Larger depths are generally difficult to be applied. Very high to high irrigation frequency is commonly adopted.

Micro-irrigation systems apply from very small depths, such has few millimetres several times in the day, up to 15- 20 mm for intervals of 2 or 3 days. These systems may be used for larger intervals when applied for supplemental irrigation in orchards and vineyards.

The irrigation scheduling methods reported above may be used to define irrigation timings and depths as follows (Table 8.18):

(a) *Crop appearance and soil moisture feeling* methods are often used when large irrigation depths and low frequency irrigation are practised. Generally, such empirical scheduling is less appropriate for sprinkler and micro-irrigation systems. Farmers base decisions on their knowledge to apply irrigations at planting and at the critical crop stages. However, the method is inefficient when a new crop is introduced and farmers do not know by experience when stress has to be avoided. In case of limited water supply, scheduling includes delaying irrigations during the development stage for enhancing root development and cutting irrigation some time prior harvesting for crops harvested at maturation.

(b) *Soil water observations* are very useful to support farmers' decisions using a target irrigation threshold, generally called soil water management allowed depletion (MAD). When only soil water potential is observed this threshold is used to define the irrigation timing, and approximately constant water depths are adopted. When observations of the soil water content are performed, decisions on both timings and depths are allowed. The MAD changes from crop to crop and with crop stages, and depends upon the water availability for irrigation. Higher soil water depletion is allowed when the available water is limited. The MAD may be based on recommendations in guidelines and the literature or, rarely, be defined using an optimisation procedure when deficit irrigation is adopted. MAD values have to be defined in accordance with the irrigation method and in agreement to the depth constraints imposed by the irrigation systems as mentioned above. When reduced irrigation is applied MAD is not used but soil water observations are useful to help deciding when to irrigate and how much water to apply to minimise the impacts of water deficits. Generally, requirements for external support are limited since the technology involved is easy to be implemented in large farms. For small farms, these methods are feasible when regional or project irrigation management programs are implemented and observations are performed in selected demonstration farm fields.

(c) *Crop stress indicators* are generally used for cash crops but, as for canopy temperature indicators, they may be also used for field crops. Crop stress indicators provide for the decisions on the irrigation timings. Approximately constant water depths are used in accordance with the constraints imposed by the irrigation systems and leaching requirements. Irrigation thresholds are specific to the crop sensing tool utilised and vary from crop to crop, crop stage and irrigation depth or frequency. Thresholds are lowered when water is limited and may be optimised when deficit irrigation is used. Crop stress indicators are useful to decide interventions that minimise impacts on yields when reduced irrigation is applied in case of drought. They are particularly useful for tree crops. These irrigation scheduling methods do not adapt well to small farms but to large

TABLE 8.18. Irrigation management for coping with water scarcity when farmers are in control of irrigation timings and volumes

Managerial information/target	Irrigation frequency	Irrigation depth	Applicability
Crop appearance			
Crop observation and knowledge of crop critical stages by farmers	▪ irrigation at planting if required to crop emergence ▪ first irrigation delayed for root development ▪ extended irrigation intervals but avoiding heavy stress at critical crop growth stages	▪ surface irrigation: large depths dictated by system conditions, ▪ sprinkling: depth selected to refill the root zone under constraint of system characteristics	▪ field crops ▪ surface irrigation and set and raingun sprinkler systems
Observed soil water			
Management allowed soil water depletion (MAD). The MAD changes with crop stages and water availability	▪ irrigation when the MAD threshold is attained ▪ low irrigation frequency for surface irrigation ▪ high irrigation frequency for micro-irrigation and lateral move systems	▪ surface irrigation: depths dictated by system conditions ▪ sprinkling and micro-irrigation: depths according to system characteristics	▪ for most crops and cropping conditions ▪ for most irrigation methods
Observed crop stress indicators			
Crop stress thresholds specific to crops and sensed data. Thresholds are lower when limited water is available	▪ irrigation timings when thresholds are attained ▪ low irrigation frequency for surface irrigation ▪ higher frequency for micro-irrigation and lateral move systems	▪ surface irrigation: depths dictated by system conditions ▪ sprinkling and micro-irrigation: depths according to system characteristics	▪ Most crops, more often cash crops ▪ More often for sprinkler and micro-irrigation ▪ Technological expertise
Climate information			
Daily or several-day information on evaporation and/or crop ET to estimated several day crop water consumption	▪ irrigation dates decided when cumulated ET equals the target depth to be applied ▪ frequency according to irrigation method used but lower when water is limited	▪ surface irrigation: large depths dictated by system conditions ▪ sprinkling and micro-irrigation: depths according to system characteristics	▪ most crops and irrigation methods ▪ easy for climates where rainfall is negligible during irrigation season
Water balance information			
Weather data (ET and rainfall) to compute irrigation needs and. actual irrigation data used to update the water balance. Targets may be an acceptable yield reduction or the MAD	▪ irrigation dates decided when the cumulated soil water depletion equals the target depth to be applied ▪ frequency in accordance with irrigation method used but lower when water is limited	▪ surface irrigation: large depths dictated by system conditions ▪ sprinkling and micro-irrigation: smaller depths in accordance with system characteristics	▪ for every crop, cropping system and irrigation method ▪ more effective when water balance models are used
Real time irrigation scheduling models			
Target as above but may be fixed using economic thresholds. Computations updated with irrigation and soil data observed in the field	▪ irrigation frequency as above but more accurately computed	▪ irrigation depths are controlled and monitored but responding to system constraints	▪ commercial farms with technological capability ▪ use of information systems including through the Web

and commercial plantations because they generally require high technological level and expertise.

(d) *Information on weather data*, such as daily or several-day information on evaporation or ET, is useful to estimate crop water consumption during that period and, therefore, the irrigation amounts and dates in agreement with the characteristic of the irrigation system used. Generally, the irrigation timings are decided when cumulated ET equals the target depth to be applied. The irrigation frequency may be lower when water supply is limited. It applies to surface irrigation, sprinkling and micro-irrigation. It is easier to adopt in climates where rainfall during the irrigation season is negligible. Best use is made when farmers are linked to a network information system, namely using broadcast or written periodic information. It can also be used by small farmers when information is given to the community but not expressed in mm but in the units used by farmers.

(e) *Water balance information* resulting from weather data input to a water balance model to compute the irrigation requirements is probably the most often used approach. The water balance may be performed using simple hand written check books, computer spread sheets, or simulation models. Irrigation data observed by the farmer – date and estimated volume applied - is used to update the water balance. Irrigation time intervals are decided when the computed soil water depletion equals the target depth to be applied or, if models are used, when it equals the MAD threshold. The frequency is lower when the water supply is limited. The method is best applied when daily crop ET and rainfall are available in real time as mentioned below. Water balance information is often supported by some kind of irrigation management programs at regional or project scale and requires appropriate means to diffuse information, as well as some support to farmers to help them converting general information into the one they specifically need. For small farms, the use of demonstration farm fields is very convenient.

(f) *Real time irrigation scheduling models* constitute a step further in sophistication and accuracy relative to the methods mentioned under (e). The models are applied to each farm field. Computations are updated using irrigation data provided by the farmer and actual daily crop ET and rainfall made available through an information system to which the farmer is connected. Model simulations indicate the best irrigation timings and water depths to be applied. Target thresholds are established for maximal yields, for an acceptable yield reduction or, when yield data are not available, a pre-selected MAD is adopted. However, when required, the irrigation scheduling criteria can be easily modified during the course of the season. Coupling an economic optimisation model to the water balance simulation model is also feasible and helps establishing the optimal target thresholds. This method applies to commercial farms with technological capability when a model is fully operational at the farm level, but it can also be used by farmers linked to an information network. Developments are being made to provide access to the model and operate with it through a Web site and GIS in such a way that soil and water-table conditions may be an input to the model with a minimal intervention of the user. However, information is improved if some observed soil data may be used to check/correct the model simulation during the course of the season. When a computer is available at the community level and adequate support is provided, including through demonstration fields, the method may also be applied to small farmers.

The brief methodological review presented above shows that the implementation of irrigation scheduling practices require efforts that imply the involvement of water and

agriculture management institutions, farmers organisations, water user associations, and ONG's to stimulate farmers and the providers of the technologies to make use of them. In other words, to just say that farmers have to adopt improved scheduling methods is not appropriate. Farmers do it when they understand the benefits, are informed, receive appropriate support and the communities are involved. Thus, before adopting new technologies for irrigation scheduling it is necessary that problems to be solved in a given location be clearly identified, objectives be set, tools and means be made available by the government, the market or any other institution. Then farmers apply an improved schedule that will increase water productivity, control environmental impacts, save water and increase agricultural incomes.

However, as said in the precedent sections, irrigation scheduling, particularly reduced demand scheduling and deficit irrigation are constrained by the performance of farm systems. When traditional poor surface systems are not improved or modernised, farmers can not apply rational scheduling because negative impacts of the system performance are higher than the positive consequences of the enhanced scheduling. When surface delivery schedules are rigid and provide unreliable and inequitable service, there are no conditions for the farmers to improve the systems and respective management. When farmers move to sprinkler or to micro-irrigation systems and receive a poor service from the dealers in terms of quality of material, inadequacy to the farm conditions and poor design, and do not have support to make a better system selection, their efforts to enhance the system performance find limits that reduce impacts of improved schedules. Therefore, it is important that the non-agricultural water-users and decision-makers know that there is a large panoply of tools and practices that may be used by farmers but they can only effectively use them when farm systems and scheduling are improved in an integrative way. On the one hand, farm irrigation is constrained by the off-farm systems and respective management. On the other hand, the application of technological advances requires adequate support to farmers.

8.8.5.3. Deficit irrigation

Deficit irrigation, as mentioned before, is an optimising strategy under which crops are deliberately allowed to sustain some degree of water deficit and yield reduction. Deficit irrigation is a sustainable issue to cope with water scarcity: it provides for application of leaching requirements to cope with salinity; the optimisation approach leads to economical viability; the allowed water deficits favour water saving, the control of percolation and runoff return flows, and the reduction of losses of fertilisers and agro-chemicals. The adoption of deficit irrigation implies appropriate knowledge of crop ET, of crop responses to water deficits, including the identification of critical crop growth periods, and of the economic impacts of yield reduction strategies. Therefore, appropriate deficit irrigation requires some degree of technological development to support the application of irrigation scheduling techniques.

Deficit irrigation requires the adoption of appropriate irrigation schedules. These are built upon validated irrigation scheduling simulation models or based on extensive field trials. Field trials essentially concern the evaluation of the impact on yields resulting from different irrigation depths and timings. The literature reports on quite a number of such experimental findings but, unfortunately, many of these papers are not producing results oriented to the farmers practice nor including economic considerations. Field trials often include the assessment of the joint effects of water and fertiliser amounts, mainly nitrogen, since water

productivity and fertiliser efficiency are closely linked. When strategies for deficit irrigation are derived from multi-factorial field trials, the optimal irrigation schedules are often based on the concepts of water-use efficiency and water productivity (discussed in section 8.2 and 8.7.1.). Experimental studies oriented to the supplemental irrigation of wheat or pulses often include the assessment of planting dates since the water productivity is influenced by the rainfall use by the crop, which varies with the planting date as referred in the section 8.7.2.

The irrigation scheduling strategies for deficit irrigation may be designed through using irrigation scheduling simulation models after these have been calibrated or validated for the local conditions. These models must include appropriate yield-water functions or crop growth and yield sub-models to evaluate the yield impacts of water deficits. When calibrated using field trials data, those simulation models are particularly useful to extend field results to other areas and other soil types. However, it is also required that economic results be associated with water use and yield data to evaluate which reduced demand strategies are economically viable. Such economical analysis are generally lacking and extrapolations from other studies are difficult because costs and benefits change with farming systems, labour, production factors and water prices, while benefits vary with the price of the harvestable yields and local markets. Summarising, there is a great uncertainty and risk in the decision process relative to deficit irrigation. More research is therefore required and better information has to be produced to support farmers decisions.

Two examples of deficit irrigation studies in Central Tunisia are shown here, one relative to a cereal crop, wheat, and the second to a cash crop, potato (El Amami *et al*., 2001; Zairi *et al*., 2002). Selected results for the wheat crop are given in Table 8.19 relative to surface and sprinkler irrigation under both average and drought demand conditions.

TABLE 8.19. Response of the wheat crop to deficit irrigation strategies considering sprinkler (NID = 40 mm) and surface irrigation (NID = 100 mm) in Central Tunisia (adapted from Zairi *et al*., 2002)

Demand conditions	Deficit irrigation strategies	Net season irrigation (mm)	Relative ET (%)	Relative yield loss (%)	Gross margin (USD/ha)	Gross margin (USD/m^3)	Percent surface allocated to each irrigation strategy
Sprinkler irrigation							
Average	SC	200	97.1	0.0	1141	0.570	100/SC
	DI	120	84.0	13.1	993	0.827	100/DI
	VLID	40	68.2	28.9	793	1.982	(100/VLID)
	Rainfed	0					100/R
Drought	SC	280	97.1	0.0	1225	0.437	100/SC
	DI	200	84.1	13.0	1051	0.525	100/DI
	EID	80	59.1	37.1	669	0.836	100/EID
Surface irrigation							
Average	SC	200	97.1	0.0	1130	0.565	100/SC
	DI	100	80.2	16.9	938	0.938	100/DI
	Rainfed						100/R
Very High	SC	300	99.1	0.0	1221	0.407	100/SC
	DI	200	83.4	13.0	1025	0.513	100/DI
	EID	100	62.7	34.4	713	0.713	100/EID

For sprinkling, results show that the net application depth required to avoid yield losses for average demand conditions is 200mm but it increases to 280 mm under drought. As expected, when decreasing the season irrigation depths evapotranspiration (ET) is reduced and the relative yield losses increase. Because yields decrease with ET also the gross margins per unit surface, expressed in USD/ha, are reduced. However, because less water is used, the

water productivity and the economic productivity of the water increase, quite drastically in case of average demand. Therefore, for both the average and drought situations, the percentage of area allocated to each of the deficit strategies is 100 %. However, results show that under average demand the rainfed crop is feasible while for drought conditions the feasibility of wheat production is limited to a supplemental irrigation strategy where 80 mm net irrigation are applied. For surface irrigation results are similar but the gross margins are different (Table 8.19). This indicates that the structure of costs vary from one irrigation method to the other.

For potato (Table 8.20) results are different from those for the supplemental irrigation of wheat due to the structure of costs and yield prices and because wheat uses a much larger proportion of rain than potato, which crop season develops after the winter rains. Thus, for the average year, reducing the net irrigation produces a yield decrease and a consequent diminution of the gross margin per hectare cropped. However the increase in water productivity is enough to produce an increase in the gross margin per m3 of water applied making it feasible to crop applying only 40 mm net irrigation. On the contrary, for drought conditions, because rainfall is much less, the increase in water productivity do not compensate for the stress conditions created when less than 200 mm are applied (strategy LDI): both gross margins per unit surface and per unit of water applied decrease, thus indicating that when less than 200 mm are available the best strategy is to reduce the surface cropped in proportion to the available water and apply there 200 mm net irrigation.

TABLE 8.20. Response of the potato crop to deficit irrigation strategies using set sprinkle systems (NID = 40 mm) in Central Tunisia (adapted from Zairi et al., 2002)

Demand conditions	Deficit irrigation strategies	Season irrigation (mm)	Relative ET (%)	Relative Yield Loss (%)	Gross margin (USD/ha)	Gross margin (USD/m^3)	Percentage surface allocated for each irrigation strategy
Average	SC	160	94.0	0.0	2331	1.46	100/SC
	LDI	120	84.6	10.4	1790	1.49	100/LDI
	DI	80	76.1	19.7	1311	1.64	100/DI
	LID	40	65.5	31.3	701	1.75	100/LID
Very high	SC	240	96.0	0.0	2343	0.98	100/SC
	LDI	200	89.1	7.7	1959	0.98	100/LDI
	DI	160	76.5	21.5	1227	0.77	80/LDI
	LID	120	71.8	26.7	985	0.82	60/LDI
	VLID	80	61.7	37.8	402	0.50	40/LDI
	EID	40	51.0	49.6	-219	-0.55	20/LDI

This last example identifies the most common solution to cope with drought: to reduce the irrigated area in proportion to the available water and irrigate that reduced cropped surface adopting a feasible irrigation scheduling strategy.

8.9. Supply management

The importance of supply management strategies to cope with water scarcity is well identified in literature and observed in practice, particularly for surface irrigation systems which constitute the majority of large and medium water systems in water scarce regions.

When the improvement of farm irrigation systems was analysed in the previous sections

it has been shown that the role of farmers in reducing the demand is limited both by the farm system constraints and by their capabilities to be in control of the discharge rate, duration and frequency of irrigation. These limitations are probably more important relative to deficit irrigation because farmers require some flexibility in the deliveries to decide the optimal irrigation timings and depths, as well as that deliveries be reliable, dependable along the irrigation season and equitable among upstream and tail end users. Therefore, the adoption of reduced demand strategies largely requires improved quality of supply management.

Supply management is generally considered under the perspective of enhancing reservoir and conveyance capabilities to provide higher reliability and flexibility of deliveries required for improved demand management. This is true not only for irrigation systems as mentioned above but also for non-agricultural water uses as analysed in previous sections. Therefore, supply management includes:

- *increased storage capacities*, including large reservoirs with capacities for inter-annual regulation, and small reservoirs, namely for supplemental irrigation,
- *improved conveyance and distribution systems*, including compensation and intermediate reservoirs for improving the flexibility of deliveries and avoiding system water losses during periods of low demand, as well as improved regulation and control, including automation and remote control, to favour that deliveries match the demand,
- *good maintenance* of reservoir and conveyance systems, which is a pre-condition for water saving and the reliability of deliveries, and
- the development of *new sources of water supplies* to cope with extreme conditions of water scarcity, as it is the case for droughts.

Supply management is also considered under the perspective of systems operation, particularly related to delivery scheduling, thus including:

- *hydrometeorological networks*, data bases and information systems to produce appropriate information for effective implementation and exploration of real time operation of irrigation systems,
- *agrometeorological irrigation information systems* including tools for farmers to accede to information, often comprising GIS, to support local or regional irrigation management programs, as well as decision support systems serving the reservoir operation, the water system management, and the users to select crop patterns, irrigation scheduling and irrigation systems, and
- *planning for droughts* to establish allocation and delivery policies and drought operation rules.

Supply management for irrigation also refers to the farm water conservation, as indicated in Table 8.21. In dry semiarid and arid zones, water harvesting plays a central role. In other water scarcity areas different issues may be considered.

The management of irrigation and multi-purpose water supply systems to cope with water scarcity includes the utilisation of a variety of managerial techniques and tools that are summarised in Table 8.22 and described below. Particular references are made to irrigation systems because these systems are the most frequent and larger water systems in water scarce regions. However, outlined issues also apply to municipal and industrial uses with due adaptations to the respective operational conditions since these systems are generally pressurised, have centralised control, and operate regularly throughout the year.

TABLE 8.21. Supply management for water conservation in agriculture

Objective	Technology
Increased storage	small reservoirs for runoff storage groundwater recharge from excess runoff
Increase water yield	water harvesting vegetation management to control runoff
Increased use of rainfall	spate irrigation micro-catchments, land forming terracing conservation tillage
Add to available supplies	unconventional water systems reservoirs, conveyance and intra-basin transfers

Management issues to cope with water scarcity may be considered in four main groups:

(a) *Additional emergency supply for drought mitigation,* which concern the exceptional use of waters during periods when the normal sources for the storage, conveyance and distribution are insufficient to meet the demand. These periods are limited in time such as the duration of a drought, but the operation of these additional sources has to be planned in advance to be effective and to prevent negative impacts on health and on the environment.

1. *New sources of surface water,* including the use of the dead storage in reservoirs and short distance water transfers from nearby systems and or sub-systems, generally associated with negotiations of water rights among farmers and non-agricultural users, including for nature, recreation, municipal and industrial uses. Since most of surface water sources in water scarce areas are already developed and water rights assigned, the use of additional waters requires appropriate planning and institutional framework.
2. *Increased groundwater pumping,* changing from the exploration of the perennial yield to the mining yield. A continuous mining of the groundwater is not sustainable but a controlled use of the mining groundwater yield during periods of water scarcity is sustainable when appropriate planning, management and monitoring are adopted, as discussed in Section 6.2.
3. *Transfer of water rights* between users, where those having the right for a given fraction of stored volumes sell temporarily these rights to other users. This applies to societies where individual water rights are well recognised by law, thus being of difficult application in other societies.
4. *Use of low quality water and reuse of wastewater* for irrigation of agricultural crops, and landscape, including lawns and gulf courses, in addition or in alternative to water of good quality. Aspects relative to the safe use of these non-conventional waters are dealt in Sections 7.2 and 7.3.
5. *Develop conjunctive use* of the surface waters that are mobilised through the existing water systems and the waters from emergency sources such as groundwater mining and non-conventional waters mentioned above. Adopting a conjunctive use approach provides for rational and sound water resources allocation (as discussed in Section

TABLE 8.22. Management of irrigation and multi-purpose supply systems to cope with water scarcity

Management techniques	Benefits	Applicability
Add to supply for drought mitigation		
▪ New sources of surface water, short distance water transfers	▪ Increase local water availability	▪ Difficult, needs integrated planning
▪ Increased groundwater pumping	▪ Adds to normal water sources	▪ Needs control/monitoring
▪ Transfer of water rights	▪ Re-allocation of available water	▪ In accordance with existing water laws
▪ Use/reuse of low quality water for irrigation and landscape	▪ Alternative sources of water	▪ Depending on crops and uses. Monitoring required
▪ Conjunctive use	▪ Maximises use of available rainfall and water resource	▪ Needs appropriate planning and management
▪ Reinforce the use of other non-conventional waters	▪ Prevents extreme scarcity	▪ Where non-conventional waters are already in use
Improved reservoirs operation		
▪ Information systems, including remote sensing, GIS, models	▪ Information for optimised operation and management	▪ Non limited but expensive for small schemes
▪ Hydrological forecasting and drought watch systems	▪ Improved assessment of supplies	▪ At large scale, large projects or regional level
▪ Upgrading monitoring	▪ Improved use of operation tools	▪ General but involving costs
▪ Application of optimisation, risk, and decision models	▪ Optimised management rules; and water allocation	▪ Non limited but expensive for small schemes
Conveyance and distribution systems		
▪ Canal lining	▪ Avoidance of seepage losses	▪ Limited by costs
▪ Improved regulation and control	▪ Higher flexibility, better service and reduced operation losses	▪ Needs investment and technology
▪ Automation and remote control in canal management	▪ Improved delivery management and low operation losses	▪ High technological requirements
▪ Low pressure pipe distributors	▪ Reduced spills and leaks, higher flexibility, easier water metering	▪ Limited by costs but easy to implement
▪ Change from supply oriented to demand oriented delivery schedules	▪ Favours farmers to apply water saving irrigation management	▪ Needs communication tools
▪ Intermediate storage (in canal, reservoirs, farm ponds)	▪ Increased flexibility and reduced operation losses	▪ Requires investment and management tools
▪ Involve farmers in delivery schedules planning to cope with limited supply	▪ Allows farmers to adopt best management practices	▪ Needs appropriate institutional arrangements
▪ Adopt demand delivery scheduling in pressurised systems	▪ Higher flexibility for water savings at farm	▪ Only constrained by the system characteristics
▪ Water prices in relation to volumes of water diverted and times for use	▪ Induce farmers to save water and to irrigate by night (automation)	▪ Requires appropriate water metering and water pricing
▪ Information systems	▪ Provides for optimised operation maintenance and management	▪ General but primarily to large schemes
▪ Application of optimisation methods to schedule deliveries	▪ Increased reliability and equity, and reduced farm demand	▪ Needs feed-back information from farmers
Maintenance and management		
▪ Effective systems maintenance	▪ Avoids spills and leaks and improves operation conditions	▪ Requires planning and trained staff
▪ Water metering	▪ Data for operation and billing	▪ Requires equipment
▪ Monitoring system functioning	▪ Identification of critical areas and system losses	▪ Requires planning and staff
▪ Assessment of system performances (physical, environmental and service)	▪ Provides follow-up on water saving programmes	▪ As above
▪ Personnel training	▪ Allows to implement more demanding technologies	▪ General, not highly costly when well planned
▪ Information to farmers and other users	▪ Knowledge on the system constraints and saving issues	▪ General

6.7) and maximises the use of the available rainfall in addition to the diverted water resources. Nevertheless, conjunctive use requires appropriate management of the water systems and good technological operative conditions.

6. *Reinforcing the use of non-conventional waters* such as rainfall harvesting for domestic uses –drinking water cisterns – and fog collection, referred in Section 7.5. These issues apply to areas where water collection systems are already available and in use since during drought they may not mobilise the required water quantities.

(b) *Improving reservoirs operation* for controlling water losses, mainly operational losses, and better allocate the available water. In few cases, measures may include changes in equipment that control releases but most of improvements concern management. Several aspects relative to the improved use of surface waters are discussed in Chapter 5, particularly relative to small systems and reservoirs. Issues include:

1. *The use of information systems and modern technologies* such as remote sensing, GIS, and models that provide for the state variables relative to the reserves in storage and to the uses and demand. Information systems are essential to appropriately explore reservoir decision tools mentioned below and to create information relative to users decisions in agreement to the water availability.
2. *Hydrological forecasting and drought watch systems* that allow for real time, or near real time prediction of reservoir inflows, evaporation and seepage, thus to better estimate the time evolution of storage that dictate the operation rules. Reservoir losses are discussed in Section 5.2. These management tools may also be useful to estimate how the demand will evolve when appropriate feedback is developed with canal managers in case of irrigation uses. Then, the support by information systems is particularly useful.
3. *Upgrading monitoring of reservoir inflows and releases* to better support the adoption of information tools mentioned above.
4. *Application of optimisation, risk, and decision models* to reservoir operation, to define optimised system management rules and to decide the allocation of water resources among the different users – municipal, irrigation, industrial, recreational, energy and nature. A large panoply of such tools has been made available by research, many are in use, but their adoption under water extreme water scarcity still is low due to the difficulty in gathering the information required to optimise decisions.
5. *Changes in reservoir water release equipment* for more accurate control of volumes supplied, easy adjustment of discharges in the course of the time, and adopting automation when decision models are effectively operating in real time.

(c) *Improving conveyance and distribution systems,* which refers both to equipment and management software. An enormous amount of research has been recently devoted to these subjects and a very large number of papers and books refer to these matters, particularly for irrigation systems. Approaches that help coping with water scarcity are generally oriented to control seepage and operational losses, to provide for higher flexibility in water deliveries to irrigated farms, and to improve the levels of service by matching supply to demand, increasing the reliability of supplies and enhancing the dependability of deliveries along the operation season and the equity of the distribution in the areas served. Main issues relate to:

1. *Canal lining* to avoid seepage losses. However, canal lining is only fully effective

when canal management is improved, maintenance is carefully and timely performed, and other canal structures are also improved for enhanced conveyance and distribution service. Otherwise, investment costs may not be justified and resulting water costs may be excessive for farmers if the water service remains at low performance levels.

2. *Improved regulation and control* of canal and pipeline systems, including local or centralised automation, generally permits higher delivery flexibility and improved conditions at farm level to adopt water saving irrigation practices as discussed in Section 8.8. Adopting appropriate regulation and control provides for reduced operation losses and for easy maintenance since water levels vary much less during operation. In general, reliability, adequacy and equity of deliveries are enhanced, while dependability depends upon the policies for reservoir management. Increasing the levels of service give better opportunity to farmers to adopt improved farm irrigation, and to include practices that lead to water conservation and saving, as well as to control environmental impacts, specially in saline environments. Appropriate regulation and control is probably the most important issue for irrigation and multipurpose water systems. However, regulation and control systems may be expensive and require technological capabilities to be fully explored despite local control automation may be easy to adopt and apply.
3. *Automation and remote control in canal management* is a step further in technological advancement in regulation and control. Remote control allows a better operation of the system particularly to take into consideration the users demand in real time. The appropriateness of these technologies to cope with water scarcity relate to improved water service, more easy application of irrigation scheduling and the farmers ability to improve the water use leading to higher water productivity and water saving. Because high technology is required and the demand has to be known in real time, these technologies adapt better to systems serving large and commercial farms.
4. *Adopting low-pressure pipe distributors* in surface irrigation systems instead of open channels and ditches is an effective solution to reduce spills and leaks, to achieve higher flexibility and service performance, and to easily adopt water metering. The investment costs may be compensated by lower operational costs when compared with open channel distributors. Benefits at farm level are once again related with the flexibility in the deliveries. This technology has no particular technological requirements.
5. *Changing from supply oriented to demand oriented delivery schedules* is the desirable orientation of system management when regulation and control are enough reliable. In fact, demand oriented delivery schedules assume that managers give priority to satisfy the demand rather than optimising the supply service. Thus, it makes possible that farmers apply improved irrigation schedules to save water and increase water productivity. It requires that regulation and control be modernised and some kind of communication between farmers and managers is adopted. This communication may be performed through direct contact between farmers and canal operation personnel, by phone or via computer.
6. *Intermediate storage* in canal reaches, small reservoirs linked with selected canal nodes, or farm ponds are often used to increase the flexibility of the system to respond to variations in demand, to reduce operation losses during periods of reduced

water use such as the night-time and holidays, and to permit the use of farm irrigation systems having discharge and duration requirements different of those provided by the delivery schedule practiced. The latter is the case of farms adopting micro-irrigation or sprinkling where distribution systems adopt delivery schedules designed for surface irrigation.

7. *Involving farmers in decisions to change delivery schedules dictated by limited supply*. During periods of limited water supply the delivery schedules have to be modified in order to satisfy the priority uses and to enforce restrictions for other uses (see Section 8.1.3). When farmers are involved in the decision process that leads to modify the delivery schedules, or to fix the respective water quotas, the farmers may negotiate these emergency measures in order to adopt the best practices that accommodate with water constraints to be enforced. This involvement may be difficult in systems serving a large number of small farms but the involvement of farmers in this decision is important for the effective adoption of emergency water saving programmes.
8. *Adopting demand delivery scheduling in pressurised systems* because this is generally the most appropriate for the required flexibility to the farm use of sprinkler and micro-irrigation systems. As analysed above (Section 8.8) these systems may be managed for a variety of irrigation depths and frequency, thus for adopting water savings at farm too. When water supply is limited and restrictions to the demand have to be enforced the respective decisions should better involve the farmers. However, adopting rigid schedules in pressurised systems generally do not lead to easy adoption of savings at farm level.
9. *Adopting water prices that induce farmers to irrigate by night* is a policy particularly appropriate for pressurised systems but that can also be used for open canal systems when some kind of metering is adopted. It consists in differentiating the day-time and night-time water prices to induce night irrigation, which gives larger flexibility to the system operation, improves the service performance and reduces operational losses due to excess water flowing in the systems at night, when the demand is lower. In addition to metering, automation of farm systems is also necessary.
10. *Adopting water prices that induce farmers to save water* may be an appropriate policy for pressurised systems where metering is available. It can also be used for open canal systems but its application is then quite difficult. It consists in water prices that vary in accordance with the water use, which increase after a given volume is diverted to the farm. The price structure ideally varies with the type of crop following policies on cropping patterns, and with the available supply, both affecting the minimum volume and the rate for increasing the prices. Water metering is essential for a fair application of this policy. Systems where water costs are associated with the land surface cropped may adopt alternative pricing policies differentiated by crop and water volume but its enforcement requires appropriate field surveys to check the areas declared by the farmers.
11. *Information systems* may play an important role when decision models are used for systems operation or to help farmers selecting the respective management to cope with water scarcity. Information systems are particularly useful to identify the state variables of the system, inclusive in real time, thus providing for better matching deliveries to demand. Information systems are even more useful in multipurpose systems to support decisions on allocation of water by user sectors, especially when

the management of the reservoir and the conveyance and distribution system are linked.

12. *Application of optimisation tools for water allocation and to schedule deliveries* is a technique that complement those modelling and decision tools mentioned before. Difficulties in application are due to insufficient economic information to adequately perform optimisation, and to the required feed-back information from the users. However, when it is possible to be applied, it may support achieving higher reliability, adequacy and equity in deliveries and the enforcement of water saving.

(d) *Systems maintenance and management* are essential to cope with water scarcity. When these are adequate, they provide for controlling water wastes, seepage and water spills and provide for water saving. When maintenance and management are poor, not only system losses are high but the water service is poor, less reliable and non-dependable, tail end users receive the poorest service and incentives for the users to save water are lacking. Issues relate to:

1. *Effective systems maintenance,* which is required not only to avoid seepage, water spills and leaks but for adequate operation of the hydraulic structures, regulation and control, and good service to users. Maintenance needs trained personnel and equipment as well as planning. Particular attention should be paid to periods when water supply is limited, when all available water is insufficient to meet the demand.
2. *Water metering* - flow depth and discharges in surface systems and pressure and discharges in pressurised systems - is required to support operation and, at outlets and hydrants, for billing the users. Data from metering also provides basic data on system variables useful for management. The adoption of information and decision support tools mentioned above is not possible without metering at critical nodes of the system and, for more advanced technological levels, without metering the water deliveries to users.
3. *Monitoring* system functioning and system performances is required to identify the critical reaches of the conduits and canals and service areas and to provide the follow-up of maintenance programmes, improvements in equipment, implementation of upgraded management tools, as well as the quality of service provided. Monitoring allows to quantify system losses, priority areas for improvement and to evaluate upgrading programmes. Data produced are an essential input to information systems and decision support tools in addition to metering. As for metering, monitoring do not produce water savings but is essential for their effective implementation.
4. *The assessment of the system performances* - physical, environmental, economic and service performances - provides for the evaluation of the actual functioning of the systems complementing monitoring and metering. Actual indicators are useful for planning modernisation, rehabilitation and betterment of the systems and are generally useful to base decisions required for implementing such programmes, consequently for planning for water saving and conservation.
5. *Training of personnel in operation, maintenance and management* is required to enhance the quality of service, for technological upgrading of the systems and to carry out water saving programmes. Training is also necessary to develop skills required to contact with the public and for the communication with users.
6. *Users and farmers information* is of paramount importance to increase the awareness

of the value of the water and the importance of water savings. Information is required to involve farmers and other users in water saving and conservation programmes. The need for increased awareness, education and training is discussed in Chapter 10. Information is considered herein as comprising training and participation in the decision making process, as it is desirable and achievable in case of farmers. On the one hand, there is the need for training and assistance to farmers to improve on-farm irrigation systems and scheduling, and to implement water conservation and demand reducing practices. On the other hand, measures have to be adopted to implement effective farmers' participation in decisions relative to supply management. This includes the information to farmers on characteristics and limitations of the water supply systems.

8.10. Conclusion remarks

This chapter outlines a large number of practices and managerial tools for water conservation and saving to cope with water scarcity. First, these practices and tools are presented in very general terms in relation with the different water scarcity regimes identified in chapter 2: natural aridity and drought, and man-made desertification and water shortage. Later, these water conservation and saving issues are dealt with more detail relative to the main water use sectors. However, in that last analysis there is no focus on the source for water scarcity.

Most of water conservation and saving practices and tools are known from professionals in the respective domains. Many of them are already practiced by many communities world-wide. Thus the main idea herein is to have them outlined in a publication for the general public, not focusing a specific group of professionals. It is important that professionals in every water use sector know and understand how other sectors may find solutions to cope with water scarcity. This is why those issues are analysed in relation to the most common difficulties for their implementation. This is particularly the case for irrigated agriculture where a large panoply of practices and tools are available but whose application is yet disappointing. As explained above, there are reasons for that unfavourable situation. When professionals and mangers in other areas could understand why progress is not made they may favour to find more appropriate conditions.

Issues outlined do not focus the most stringent water scarcity conditions. Practices and tools must be known and selected in accordance with the problems to be solved. The practices and managerial tools have been outlined as a guide for further selecting, evaluating and implementing those more adequate to a given region or country. The adoption of water conservation and saving is not only a technological problem but involves many other considerations relative to the social behaviour of the urban and rural communities, the economic constraints, or the legal and institutional framework that may favour the adoption of some measures and not other.

Moreover, adopting water conservation and saving practices and tools requires that a better knowledge of the water scarcity regimes be developed, the water be given a social, economic and environmental value in agreement with the society, and education for water be effectively installed. For these reasons, water conservation and saving constitute just one chapter in a wider book.

9. Social, economic, cultural, legal and institutional constraints and issues

9.1. Local communities

In regions of water scarcity small communities have usually developed, over time, informal systems for water sharing, use and disposal. These systems may not be efficient or equitable but some degree of acceptance usually prevails. Problems are likely to occur in such communities when the population size changes or when new ideas are introduced or developed for water use. Cooperation is needed between individuals – in fact is vital for the survival of the system and for harmony within the community. There is usually, or there needs to be, an agreed set of expectations and operating rules. It is likely these will not have any formality, will not be written down, but will be widely accepted. Friction and upheaval is likely to occur if any newcomers to the community do not accept or adhere to the accepted practices. Hence in summary, cooperation and thoughtfulness towards others is required.

Communities in regions of water scarcity are particularly vulnerable to actions of nearby communities. For example a community which catches surface water from the few runoff events that occur during a year are likely to be adversely affected by any developments upstream either of capture of the water resource by someone else or of release of wastewater. Similarly the community itself may adversely affect downstream users. Hence care, sensitivity and cooperation is needed at all times. Similarly where a local community is dependent on groundwater, any actions it takes, or actions of others who access the same aquifer will affect all users of that aquifer. Again cooperation is required. However as the scarce water resource comes under increasing pressure, cooperation and dependence on the care and sensitivity of all involved is usually insufficient and it becomes necessary to introduce more formal agreements and even to develop institutional and legal frameworks for exploitation of the resource. Without such institutional arrangements upstream and/or economically more powerful communities will tend to dominate and jeopardize the survival of other communities. Where water is abundant such considerations may not be necessary but in regions of water scarcity, unless the population is very stable and continues traditional water use practices, problems are almost certain to occur. Without introduction of some kind of institutional arrangements conflicts are likely to be bitter and protracted.

One means of avoiding or overcoming disputes where the resource is not able to meet everyone's expectations is to innovate. There are many opportunities for local communities to either use the available water more effectively, and therefore need to consume less, or to develop additional resources. Most local communities already utilize the obvious and traditional sources of water such as the local, perhaps ephemeral, stream or groundwater. However there are often other neglected resources, which may appear small, but which in fact may be capable of increasing the water availability by a considerable amount. Most innovative water capture or exploitation opportunities for communities in regions of water scarcity are very site specific. From the list that follows there may be none applicable to some local communities but in other areas it may be that more than one of these ideas could be utilized.

Some innovations that could be utilized may be:

- Re-design of roofs to allow easy capture of roof runoff.
- Development of a receptacle-making industry for the manufacture of storage tanks to hold roof water or water from other sources while minimizing seepage and evaporation losses and discouraging disease vectors. For example in north-east Thailand the development of widespread use of ferro-cement jars and tanks with capacities from a few hundred, up to a few thousand litres has revolutionized social patterns in this region which has a 9-10 month annual dry period. Prior to development of roof catches and water jars families drifted to city-centres late in the dry season causing large social disruption. The necessity for this annual movement has been largely removed by the availability of water storage facilities for each household. These storage jars/tanks are constructed using local materials and skills, and in addition to securing a supply of potable water their manufacture is adding to the local employment base.
- Import water from a region of water abundance. This solution usually has high capital demands but may be useable in some regions (as discussed in section 7.5). It usually involves transfer of water from one basin to another and so environmental considerations may also be quite important.
- Customary uses of water may be quite wasteful. To reduce the waste may, in effect, increase the available water resource quite markedly. For example, as referred in section 8.5, where potable water is disposed from households to the sewer system and other potable water is used for urban cleansing and irrigation, some of the disposed water, with minimal treatment, could be used for the cleansing and irrigation activities, reducing the demand on the potable supply. In water scarce regions no water should be "thrown away". All wastewater, usually after only minor treatment, can be re-used for a range of non-drinking purposes.

  In some communities large amounts of water are traditionally used for (ritual) bathing. Minor changes in the location, shape and operation of bathing facilities may save significant impacts on the amounts of used water.
- Water re-use has been mentioned above and dealt in section 7.2. Many possibilities are available for water re-use. The technology is usually quite simple but large capital costs may be involved to make possible the re-routing of large volumes. Pumping costs may also be involved as systems have usually developed using gravitational flows, and re-use would usually involve redirecting flow from a point of disposal, at

the lowest elevation of the system.

- Development of a culture of care for water resources. In most communities, both in developed and developing countries, there is only very limited appreciation of the links between general everyday behaviour and water resources. Simple activities like careless disposal of wastes, or cleansing of paved surfaces with water under pressure from a hose, rather than by sweeping, are not recognised by most perpetrators as being wasteful of precious scarce water resources. There is a huge need for education to alert the public to the effects of their actions and to encourage more appropriate, water-conservation behaviour.

9.2. Urban centers

9.2.1. General

For small urban centers it may be possible to draw the water needs from the stream which passes through the town or from the aquifer below the town. However as urban developments increase in size (increased industry or larger population or both) there is often a need to obtain access to more water than is available from the local source (Morris *et al*., 1997). It is likely that both the stream and the groundwater below the urbanizing area will have become contaminated by wastewater and other effluents of (careless) human activity. Obtaining addition water may involve transfer of water from another basin. Usually when water supply is sourced from another basin the wastewater is not transported back to that other basin but is disposed in the basin in which the urban center lies. This means the downstream flow characteristics of both streams will be changed – one having its flows decreased, the other increased but with poor quality. In the past it has been common for the source basin flows to be reduced practically to zero, meaning that the environment of that river valley is changed completely. In the 21st century changes of this magnitude are usually unacceptable since they have large impacts on the local population and drastic impacts on the ecology of the stream. Similarly the stream and aquifer to which the water is added, usually in the form of wastewater, suffer changes of increased flows, changed timing of flows and a deterioration in general water quality.

9.2.2. Environmental consequences

Exploitation of groundwater from certain types of geological formations can lead to problems of land subsidence. There are many documented cases around the world (eg Custodis, 1997; Sharp, 1997) of large subsidence causing changes in surface gradients, leading to changes in flow paths for drainage and flood flows and even the development of wetlands on residential land, with the need to abandon expensive housing developments. Similarly exploitation of a resource, of either surface water or groundwater, will usually impact on already existing uses of those streams or aquifers. Careful investigation and planning is needed before new water sources are developed to avoid very costly unforeseen consequences.

9.2.3. Water re-use

Urban centers usually provide ideal opportunities to practice water re-use. Wastewater of a range of qualities is available and is usually already concentrated, or will need to be concentrated as development continues, at a few locations in the wastewater collection system (sewer). In any region where water is scarce all forms of water re-use need to be considered, from use of that water in untreated form for irrigation, to full treatment for domestic (drinking) water. Water re-use usually provides several advantages over collection of "new" water:

- the water has already been collected and is concentrated at one or a few locations;
- the quality of the wastewater is usually technically easy to improve. Bacterial and solids contamination are easy to remove, but dissolved salts of any kind are very difficult to remove;
- the cost of re-use is usually smaller than the cost of collection and treatment of "new" water.

9.2.4. Reduce evaporation

In all regions of water scarcity it is important to avoid water loss by evaporation. Wherever possible water storages should be covered, irrigation should be conducted at night and in windless conditions. Without care well over 50% of all collected water can be lost by evaporation.

9.2.5. Water conservation education

In most urban areas it is common to see large quantities of water being wasted due to thoughtlessness or carelessness. Many urban dwellers take their water supply for granted and have little appreciation of its value. Almost all urban dwellers worldwide need continual reminders of the importance of saving water. This is particularly true in areas of water scarcity. As discussed in the next chapter there is need to continually provide education to all urban dwellers, beginning with small children, concerning the need to conserve our precious water resources. People need to be shown that small changes in behaviour, such as properly closing taps, minimizing water for bathing, etc., can reduce consumption by up to 50%.

9.2.6. Pricing of urban water

In most urban areas where there is a piped supply to households the water is supplied free, or the users pay a fixed amount. World Bank has reduced its funding of water supply schemes because most governments are unwilling to charge users enough to cover the real costs of operating the supply system. As mentioned earlier (chapter 4), in regions of water scarcity it makes sense to charge at least the real cost of supply. In some cases a sensible management strategy would be to use the water supply charges to add a small amount to tax income. It is possible to arrange tariff structures so that essential water costs very little but profligate use incurs large penalties. Around the world experience has shown that water price combined with education can have a beneficial effect on consumption (Spulber and Sabbaghi, 1994).

9.2.7. Institutional framework

Without widely accepted legal and institutional arrangements concerning water supply there is likely to be either hardship for the urban population or considerable unnecessary wastage of the scarce resource. There needs to be a body or bodies with clear responsibility for development, maintenance and management of the supply system. The manager could be a public or private body, but it needs legal backing for collection and ownership of water and to be able to regulate and charge for water consumption. Without such agreed or accepted legal backing it is almost impossible to have a fair and efficient supply system. In a region of water scarcity efficient (usually meaning minimum) water use and avoidance of leakages, theft and other losses is essential. These ideal conditions can usually only be achieved when a fair, widely accepted (by the water users) legal and institutional framework of operation is in place.

9.2.8. Research

The science of optimal water use is not yet perfect and there are many areas where there are opportunities for making more efficient use of limited water resources. Irrigation offers many opportunities to use less water to obtain the same crop production. Evaporation reduction is always a challenge. Not only is research needed for these fundamental issues but there are many opportunities to save water in local situations by encouraging small changes in current practices. Research is needed both to discover where savings are possible and to find ways to encourage changing of some traditional or even culturally based practices. Research is needed by social scientists in addition to water scientists and engineers.

In most urban centers there are many opportunities to reduce use of scarce water resources. As can be seen from the above, some of these opportunities involve changes in peoples' thinking and then of their behaviour. Changes in thinking and attitudes may be needed by the city leaders and politicians, by the water managers and by all members of the community at large.

There is a large opportunity to develop water re-use. Already in most large urban areas the cost of treating water for re-use is less than the cost of collecting and treating "new" water. However research is needed to develop methods which will guarantee the safety of reclaimed water and to persuade potential users of this water that it is in fact safe.

Continued research effort is needed for treatment of water to potable quality. Costs of desalination are falling but energy sources will limit widespread use of this technology. Other low cost methods need to be found for removing dissolved salts (particularly toxic salts) and bacterial contaminants. For regions of water scarcity where settlements are small there is a need to develop methods that can be used at the household level.

9.3. Rural areas

9.3.1. Water for households and irrigation

In most regions of the world there are enough water resources to sustain small populations.

The difficulty of translating this potential into reality lies primarily in the complexities of managing the water. In most water-scarce regions supply is usually abundant during the few days of the year when there is rain or snow. How can this very short term, relative abundance be managed to provide a steady supply until the next occurrence of rain?

In general, management of scarce water resources is primarily concerned with storage of water and protection from contamination. This applies whether the immediate supply source is groundwater or a surface reservoir of some kind. In essence management is about directing the short period, relatively abundant water into some form of storage, maintaining the water in the storage, and then extracting it at a rate sufficient to meet the needs, but not at a high enough rate to exhaust the storage before the next inflow occurs.

9.3.2. Capture of available water

When rain occurs there may or may not be runoff from the soil surface. If there is runoff, infrastructure should be in place to capture this water. Use can be made of small dams across stream beds or of excavated ponds into which surface flow can be directed. As noted earlier (section 5.3.2) it is important that any constructed reservoirs should be as deep as possible, with as large a volume surface area ratio as possible. Evaporation continues to remove water from the surface of any reservoir and so it is vital that the reservoir be much deeper than the depth of water that will be removed by evaporation before the next inflow. In arid regions with high temperatures the evaporation can remove up to 4 metres of water per year. Water usage from arid zone reservoirs may be of the order of only 20% of the reservoir capacity. Evaporation and minor seepage takes the remainder. It may be worthwhile excavating a hole in the bottom of any arid zone reservoir to provide a source of drinking water for emergency situations when the interval between inflows is longer than expected. Such an excavated hole needs to be located where it will not become filled with silt from each inflow, and it needs to be cleaned of accumulated silt regularly.

A significant source of water in water scarce regions can be roof runoff or runoff from other impervious surfaces such as roads or school playgrounds. Some effort is usually required to modify roofs or impervious land surfaces to develop capture and collection systems. It may mean that traditional roof systems or roofing materials may need to be changed to facilitate water capture. Similarly water storage ideas may need to be revised. For example in the north-east of Thailand a cottage-industry has developed around the manufacture of ferro-cement water jars which range in size from 10 litres up to 3000 litres. These have the advantage that they can have small openings and so very little of the captured water is lost by evaporation and insect pests can be kept out. A roof area of 20 m^2 can provide up to 350 litres from a 20 mm rainfall event.

Some ingenuity is needed to adapt current rainwater drainage systems and to make use of locally available, low cost materials to permit capture and storage of this water. However the effort of the investigation and persuasion of people to modify their traditional practices needs to be balanced against the hardships of inadequate water and the cost of collecting that water from a distance. Roof water is collected and can easily be stored adjacent to the point of use and impervious land surfaces are usually very near to points of water use because the impervious soil surface is usually the product of the passage of many feet.

9.3.3. Education for evaporation reduction

Evaporation is relentlessly driven by solar radiation and the passage of dry air over water surfaces. Everyone living in an area of water scarcity needs to understand this. Until people understand the basic principles of evaporation they are unlikely to take any action to minimize evaporation of the precious water. The keys to evaporation reduction are the minimization of the water surface that is in contact with the air and the protection of the water from solar radiation. Water should be stored on the surface in deep reservoirs rather than in extensive, shallow basins. Total elimination of evaporation is only possible if the water is totally enclosed, as in a roofed-over man-made tank. Enclosed tanks can only have limited capacity. Ponds or reservoirs in the land surface should be located to maximize the depth surface area ratio. Similarly outside water use should, as far as possible, be restricted to times when evaporation potential is lowest – at night and when there is no wind.

These principles are unlikely to be known or practiced by the population unless they are presented to them frequently. As discussed in chapter 10 the education process needs to begin with small children and continue throughout life. Schools need to have consciousness of the means of avoiding water loss by evaporation as a basic part of their curriculum. However there is a need to ensure that those for whom school is not available, and the post-school population are also continually reminded of the fact that their survival may depend on their attention to water saving and particularly to reduction of evaporation. In regions of high evaporation there is little point in capturing water in shallow lakes and ponds. However deepening of the ponds, even over only a small part of their bed makes good sense.

9.3.4. Water harvesting

Water harvesting is commonly practiced in areas of water scarcity (see section 5.4). However there is always need to enlist and stimulate the thinking and ideas of the local population to find better ways to maximize the beneficial use of all water that is precipitated. A climate of discussion and interchange of ideas needs to be encouraged so that maximum benefits can be achieved for the community from the small amount of rain that falls. Professional, expert help can be enlisted to develop better water-use and capture methods but the local people need to be enlisted as the greatest source of ideas. There may be long-established traditional practices of water use that may need some change. It will usually only be possible to effect changes in such practices by first getting to understand the culture and traditions that surround them and then developing a sensitive, locally adapted educational program. Actions to direct or coerce changes in traditional practices are unlikely to be successful.

9.3.5. Avoidance of environmental damage

It is often thought that manipulation of water resources in water scarce regions will not have any environmental effects. In fact the opposite is more likely to be true. Any changes or management of the scarce resource is almost certain to affect other parts of the environment, most of them adversely. Any water captured for any purpose will be a deficit for the local environment. The effect may be so small as to be negligible. However in some regions capture of water for household use in a region of scarce water will reduce the water

available to vegetation downslope of the point of capture. Disposal of wastewater can have the opposite effect, encouraging growth of vegetation that is uncharacteristic of the region. More widespread and more noticeable effects must be expected from larger enterprises. The changes may be subtle and slow developing but they can be devastating for the local populations. For example disposal of nitrogen-rich water may cause eutrophication of a pond a little further downslope. Development of or changes to water supply and wastewater disposal schemes need considerable imaginative environmental planning to avoid unexpected harmful outcomes which may outweigh any benefits of the development. Examples abound.

9.3.6. Irrigation performances

Irrigation is discussed in some detail in section 8.8. In regions of water scarcity irrigation should only be practiced where high value returns can be expected and where loss of water by evaporation and seepage below the root zone can be avoided.

Since water is an extremely scarce resource it should only be used for practices which produce large or life preserving benefits. While it may not be possible to assign a monetary value to in-house water use, most of this water use is essential for the survival of the population. Similarly the monetary returns from irrigation may or may not be high but the important question to consider is whether or not the irrigation water use is vital to the survival of the local community. If water use of all types is given a utility value by the local population it should be possible to determine whether or not irrigation is in the best interests of the community. Overlying the making of such decisions are questions of ownership of water, which has to do with the constitutional, legislative and cultural traditions of the region, which are discussed below.

If irrigation is to be practiced it is essential that the crop return per unit of water used is maximized. Large efforts need to be made to minimize unproductive use of water. In other regions there may be different objectives but in areas of water scarcity these are essential aims. The amount applied needs to be such that little or none is percolated beyond the root zone. Wherever possible irrigation water should be applied in the evening, allowing all pounded water to infiltrate before the sun rises and encourages evaporation. In dry regions sprinklers should, wherever possible, only be used on windless nights. Atomisation of water into small droplets which have large surface area encourages rapid vaporisation in dry air. In low humidity, windy conditions, up to 50% of high pressure sprinkler water may not reach the soil surface, and even some of that will evaporate before infiltrating. If daytime use of sprinklers is the only option for water application, it may be better to save the water for some alternative beneficial use. Differences between the proportion of sprinkler water penetrating the root zone in daytime and night-time can be as high as 50%. Where water is highly scarce, a non-beneficial use of water of this magnitude could be considered a crime against the local people.

Modern changes to drip irrigation and sub-surface water application have distinct advantages over sprinkler, flood and furrow methods of applying water in regions of extreme evaporation potential. Changing water application methods is very expensive, so there is a need to encourage use of drip and subsurface methods for all new irrigation developments in places of high evaporation.

Research and development aimed at reducing water use in irrigation, or rather, increasing crop yield per unit of water applied, is of great importance. In all irrigation methods most of the applied water is consumed by evaporation. If this could be reduced, without reducing crop productivity, much water could be available for other uses.

9.3.7. Water rights

The issue of ownership is always important in regions of scarcity. For maximum development and harmonious relationships there must be clear and widely accepted agreement on sovereignty. In one sense water is owned by everyone. It is a natural resource. However no practical scheme has yet been devised to administer such an ownership system. In some states all water is owned by the head of state, in others it is owned by those on whose land it is found. All ownership or administration systems are human inventions and as such reflect the innate greed and selfishness of the species. No system is perfect. There are always some who are advantaged and some who are disadvantaged. This reflects the history of civilization. Some systems of ownership or tenancy or management or rights to use of water have remained in place for a long time, others have changed continually. Change must be expected. As circumstances change existing systems will be seen to be inadequate for current circumstances and changes will occur, either by discussion and negotiation or by violence and dominance, but changes will occur. Unfortunately no political system or water management policy coming from the political system is perfect. There is a continual need for water managers to improve water use efficiency either within the framework of water governance, or perhaps by working to have the water governance or ownership system changed.

At a less political level, the rules governing water resources allocation and use have huge effects on the efficiency of water use. Stable systems encourage investment in efficient water use and water application methods. Year to year leasing of water does not encourage any investment and leads to opportunistic use of water with minimal preparation or planning. Even at the small village level there are considerable advantages in having in place agreed rules concerning who has access to water, how much can they use, for what purposes can it be used, what is to be done with return water and what is to be its quality, etc. As systems become larger the need for agreed rules become much more important. But note the rules need to be widely accepted. Disagreement over any parts of the rules inevitably leads to instability and a distinct reduction in the benefits that will be obtainable per unit of water.

9.4. User groups

User is defined in the broad sense of a consumer of water. Householders who receive a supply, irrigators who extract water for their farm by pumping from a river or reservoir or who are supplied water via a pipeline are all included in this term “user”. Sometimes users are dispersed residents, commercial enterprises and farmers. Sometimes the users band together to form a group which extracts or collects or buys water which is then distributed among the group members.

For any water user group or association or cooperative to be successful it must have

some set of rules which govern its operation. These rules may be formal or informal, written or traditional but there must be some accepted mode of operation. Preferably rules should be written since unwritten rules tend to change little-by-little and almost inevitably lead to disputes. Written rules are also often disputed and need to be adjudicated in some manner. However unwritten, informal rules suffer the problem that each user has his own idea of what the rules mean, and over time those ideas change. When a disagreement occurs it becomes very difficult to find agreement on the meaning of the rules since by this time each interested party has a different understanding of what the rules are. Disputes over unwritten rules, where most parties are intent on preserving or (perhaps subconsciously) increasing their benefits become very difficult, even impossible to resolve and inevitably mean that relationships between at least some of the parties become strained or are terminated. When this happens everyone loses because the social disruption, disputation and perception of being wronged prevent further cooperative activities. Then managing the water resource has priorities which focus on social sensitivities rather than on optimal use of a scarce resource to benefit the whole community.

It sometimes occurs that a user group is effectively owner of the resource and carries out total management of the resource, from capital investment, to maintenance, to revenue collection and distribution, to protection of water quality, etc.

Institutional frameworks of user groups need to be different from place to place to fit in with the local political, legislative and cultural environment.

Development of an autocratic regime where a single person has complete authority to determine water distribution is unlikely to be acceptable in a country where there is a long standing democratic tradition and vice versa. In some situations it may be considered there is no need to develop formal rules since there is currently harmony and acceptance of the informal agreements or cooperation. However in any situation of water scarcity it is inevitable the demands for water will exceed available supply and dissatisfaction and disputes will inevitably arise. Better to have an accepted, defensible, formal system in place as early as possible.

The structure of user groups and the agreements and rules they develop for allocation and use of the scarce water resource will need to reflect the interests and needs of potential users, or customers, as they could be considered. For example what is the nature of each potential users claim to be able to appropriate a share of the water? Are they traditionally the owners of the water or users of water that belongs to everyone? In the local tradition who is the owner of the water – the monarch, the head of state, parliament, the local mayor or village headman, the landowner or the whole population? This issue must be settled before any formal arrangements can be possible. On what terms will users be able to take water – by purchase? – to the highest bidder in the market? in proportion to size of landholding? – as a land owner or also as a land renter? as a shareholder in a cooperative to which a volume of water is assigned? as a paying customer of an agent charged with managing a part of the resource? There are myriad possible arrangements, many of which either alone or in combinations could provide for efficient overall management of the resource. But as stated earlier, some formal arrangement, which is acceptable to potential users and fits in with the political and cultural context is likely to provide the most stability for the users. It will also enable the environment within which the water use must occur, and the environment from which the water is extracted, and to which any wastewater is to

be returned, to be considered early in the process, and not left to a "patch-up" requirement after environmental problems have become obvious, which almost always leads to less than efficient compromises both for the water users and the environment.

User groups will usually develop self help programs for their own benefit. Of high priority for user groups should be educational programs to assist users to develop efficient water use practices. Independent of whatever charges are levied for water use an education program should aim to convey the great value of a water resource and the value of efforts to protect and maintain the resource. For users to pay the real, full costs of managing the water resource is probably the surest way to convey this sense of value, but where there is no tradition for users to pay there is still a very important need for all to understand the true nature of the value of water.

User groups also need to support and encourage research activities to enable them to make greater use of their available limited resource. They should encourage the search for new, untapped potential sources but they should particularly be encouraging use of less water for each task and an awareness of the benefits of maintaining a high quality of all water, particularly of any water released back into the natural environment.

9.5. Administration of water use – public and private organizations

9.5.1. Types of administrative structures

Structures can be privately organized, or they can be related to government activity, or it could be there is no structure. It is common to have no structure at all when a land area is being newly settled. While the available water resource far exceeds the needs of the potential users there may be no need for any administrative structure or any real management of the resource. The resource is large and the users have little effect on it.

When water use begins to approach the available supply, either during a brief dry period or perhaps during a drought, there are usually calls from among the users, particularly from those at the fringe of the resource or those who have only simple water collection methods, for some organizational system to be developed to ensure that they are not cut off from any supply during a period of scarcity. Since water is rarely in abundant supply, and since its occurrence in time is random, following the laws of chance, there will inevitably be periods when no water is available unless action is taken during wetter periods to store some water to provide supply during dry periods.

If storage schemes are to be implemented (surface reservoirs, recharge of groundwater aquifers), should the system be that every user looks after himself, or should cooperation and community action be encouraged? In some small parts of the world, water supply is a totally private matter. Each household and other enterprise looks after its own needs. In other areas there are private companies which collect water and distribute it to those who pay. In the majority of regions water administration is a government (either local or national) activity and the governments have set up structures to manage the collection, storage and supply of water. In many cases, governments found that participatory management is the most adequate solution and the management responsibility is given to water users associations, as it often happens quite successfully with irrigation systems

(Groenfeldt and Svendsen, 2000). In yet other areas, governments have decided they do not need to be involved in such activities and have sold their water infrastructure to private companies which aim to make a profit from water. In many of these cases the water company is a monopoly and has no competitors because they own the complete (and interconnected) collection, storage and distribution system. In some of these cases government regulators are appointed to ensure the companies become neither takers of immense profits nor inefficient wasters of both the water and the funds of the users. One means of maintaining accountability of monopoly companies is for the government (therefore the people) to own a substantial portion of the shares.

In addition to the several methods of administering collection, storage and distribution of water there can be many different modes of determining how much of the available water each user may acquire. In some systems (which are not very common in areas of water scarcity, though they are not unknown) users are free to take as much as they wish provided they pay for it. For example in many large cities this is the system adopted. The supply organization undertakes to supply water in whatever quantities the user wishes and the supplier recovers all costs plus a reasonable profit margin. For this system to succeed the supply manager needs to plan many years ahead, constructing collection and storage systems to meet all needs. The manager needs access to large amounts of capital. He also needs to forecast trends in population and lifestyles (per capita water use) and to be able to influence water use activities (fashions) by using education, pricing and perhaps coercion and restrictions on supply to ensure his objectives are met. In many parts of the world it has been realized that access to unlimited supply by large populations in large cities is not necessary for human well-being and is usually very damaging to the environment of the surrounding country.

Hence in many places the aim of water supply managers has changed from supplying whatever is requested, to managing demand by use of the methods mentioned above, as discussed in chapter 8 for different uses of the water. Methods used to manage demand include making large usage expensive, using persuasion backed by environmental arguments, and where necessary restricting supply by only making water available in the distribution system for part of each day (McMahon, 1993).

9.5.2. Equity and rights

Who has a right of access to water? – to how much? – how often? In regions of water scarcity sustainability of the water resource and of the human population will only be achieved when the population regards the system as fair. Inequities can be maintained for the advantage of some over others for some time but eventually inequitable systems will be swept aside. The problem in this equity concept is how is fairness defined? What is regarded as fair by one group may be intolerable to another. Water rights reflect human rights. Human rights have some absoluteness about them, but they can never be separated from cultural considerations. Who has access to land and water ownership? Who determines where wastewater can be disposed and by whom? These are issues that will change continually over time and from location to location. Is the water I have, available for me to use and dispose as I choose or am I a steward, expected to preserve and protect my water against any possible damage or loss? Is there an agreed set of laws in my region which govern how I and my neighbours manage and use the water? Is the water a

marketable commodity available to the highest bidder with the price governed only by supply and demand? Can we allow an essential life-support resource to be controlled totally by market forces? There are myriad questions of this type. They must be answered within the context of local cultural, political and economic systems, but they must be answered. The more of these questions that are openly considered before a water management/administration system is set up in any area of water scarcity the greater the chances of the long term success of the scheme.

10. Education

10.1. Need to change attitudes to water

10.1.1. Current attitudes

In most regions of water scarcity the population has developed its strategies for survival as best it can, using its ingenuity and available skills. However as populations increase and the water resource available per person declines, and as global climate change threatens increased uncertainty concerning the size of the limited available resource, there is a need for populations to have new attitudes to water.

The general prevailing attitudes could be summarized as follows:

- water is a resource provided free by "nature",
- there will always be water available for my needs.

Unfortunately these attitudes are reinforced for the majority of the world population who live in urban environments by the reasonably efficient public water supply to which they have access. In the developed world it is taken for granted that high quality, abundant water is always available at several points within every housing unit. In developing countries, even in regions of water scarcity it is taken for granted that safe quality water is delivered to all housing units at least for a few hours every day. These regular supplies, for which the charges, if any, are quite modest, has insulated the majority of the population from any need to consider conservation of water. With a large part of the populace satisfied with, and taking for granted continuation of their water supply, there is little demand on suppliers (often government agents) from customers to improve the efficiency of their water gathering/supply operations, nor on the customers to think about water conservation and saving.

An unfortunate consequence of these worldwide circumstances is there is much waste of water by those who have access to an organized supply system, but availability of water to those who must gather their own supplies continually declines in both quantity and quality.

It can be confidently stated that in most regions of the world there is large waste of this precious natural resource due to:

- *Lack of care*. If water is always available and if it costs almost nothing a very

complacent attitude is almost certain to develop. Even for community minded people there is no encouragement or incentive to be careful with water.

- *Lack of thought*. Unless water users are educated about the scarcity of supplies and the potential for contaminating water, in rural as well as urban environments, the majority are unlikely to independently arrive at the conclusion that water supplies are being endangered by their activities. To combat this attitude deficiency there is a need for a major community educational program.
- *Lack of realistic pricing*. In most parts of the world water supplies are subsidized from general tax revenue. If all users met the actual cost of the water they used, including the costs of disposal of the waste water, there would be some small incentive for improving interest in water conservation. In regions of real water scarcity it makes sense to increase charges for water by adding a tax raising component to the water supply charges. Even if all operational and capital costs are covered by the charges, the water is still quite inexpensive. Water from organized supply systems will usually cost much less than for households to collect (and pay with their labour) and treat water themselves. However charges may not be enough to provide incentive for individuals to be water conservation minded. Clever pricing structures can be a means of drawing the real cost of water (including all the environmental costs) to the attention of everyone in the community. Experience has shown that subsidizing water supply encourages waste and eventually leads to the destruction of the scheme. It is rare that long term water supply costs, such as for operation, maintenance and debt servicing can be continually met from general tax revenue. Experience has shown that where no charges are levied on users the whole scheme progressively runs down and then an unpaid capital debt remains which prevents reinvestment to refurbish or replace the lost system. Recent experience with increasing prices per volume used has shown that consumption is quite price sensitive, even in relatively affluent urban areas (eg in Sydney, use has declined 30% after a 60% price increase over 3 years).
- *Lack of maintenance*. Water supply schemes need many kinds of maintenance activities. As the infrastructure ages the demand for maintenance increases. Realistic allowance is needed in budgets to cover the ever increasing maintenance costs. Most water supply schemes are largely out of sight (buried pipes) and are taken for granted. The most modern, best maintained schemes lose about 10% of their water by leakage and general losses. In poorly maintained schemes the losses exceed the water reaching customers. In addition to the revenue foregone by this lack of maintenance, in regions of water scarcity the squandering of more than half the resource is inexcusable – it condemns the customers to a more difficult than necessary lifestyle. Similarly in regions of rising water tables and water logging, leakage from the supply system increases the problems. Commitment to good maintenance is imperative as a key strategy for coping with water scarcity.
- *Lack of sense of ownership*. In most cultures there are proverbs or popular sayings along the lines “if I don’t own it I have no responsibility to care for it” and “if it is free it cannot be worth worrying about”. Such attitudes ensure a short life for any project. It is important that the local population regards their water supply scheme as their own. If they have a sense of ownership they will treat it well and insist that others do the same. If the scheme is seen as being owned by a remote company or the

government they are likely to feel no responsibility and to see the owner as the bearer of all costs of maintenance and repairs, even if these are the result of lack of care, or even malicious actions by customers. A sense of ownership can be encouraged by requiring customers to have a real ownership stake in the enterprise and by constant educational efforts.

10.1.2. How can attitudes be changed?

The immediate response to a question such as this is "education". But how can education be used to bring to every member of the community a sense of responsibility for the protection and efficient use of its water resources? Water use is ubiquitous but cultural attitudes to water and its usage vary greatly from region to region.

At first there needs to be some agreement on what are the ideal practices to be followed in relation to water management. Some rules or framework of agreed principles need to be put together which (at least) encompass the issues shown in the Box 10.1 below.

BOX 10.1. Questions behind the basic principles that support attitudes related to water by users and managers

- Who owns water? – rainwater, water flowing over the surface, water flowing in surface channels, groundwater.
- Who can make use of the water?
- Activities to be avoided near the community water sources – near the wells, near the pond, in the catchment. Who will supervise compliance? What will be their powers?
- How will water be collected and distributed? Who will undertake this activity? How much will they be paid? How much will be charged for supplied water? Will the price vary with quality? How to ensure everyone, irrespective of position or wealth, has reasonable access to the supply?
- After use, how will the wastewater be disposed? Who will be responsible for disposal and for environmental effects of the disposal?
- How much of the wastewater will be recycled? What uses will be made of recycled water?
- During periods of acute shortage (e.g. during drought), how will rationing of the scarce supply be managed to ensure continuation of minimum essential supplies and equity in the community?

Once agreed principles are assembled there needs to be an investigation (research) of how ideas and attitudes among community members can be changed most effectively. This is a most important step since there are large links between water and culture and tradition, and every small community has developed its own idiosyncrasies and "best" practices. The outcome of this research should be a plan for educating and changing attitudes to water and water use that will facilitate the sustainability of the community. One educational program will not suite all communities in a region, so some sensitivity and flexibility will be needed in both the development and delivery of appropriate programs. Note that education to bring about attitude change cannot be considered a task to be completed in the short term. A permanent, ongoing educational program will be needed. More details are considered later in this chapter.

10.1.3. Aims of an educational program

The aim of any water education/public relations/information/propaganda program needs to be to develop both in the community as a whole, and in each individual, attitudes which will ensure supply of water of appropriate quality and quantity to sustain the community. Attitudes needed are those which foster conservation and sustainability of existing water resources and encouragement of innovative and practical ideas to allow more effective use of the available resource. Incentives are needed to encourage individuals to seek out and develop additional resources that are economic but do not interfere with resource use by others, nor degrade, endanger or bring about unacceptable environmental changes. This thinking would need to encompass water collection and harvesting, storage, wastewater disposal and re-use, water quality issues of all types and accessibility to water.

The role of education in the above aims is to inspire everyone in the community to be thinking about water in constructive ways. If each person can be encouraged to consider how they, personally, can save water and preserve its quality, how they can contribute ideas to increase the community water resource and how they can contribute to the community effort to increase and preserve the available water resource, then the education system may be considered to have been a success. However once some success is achieved the effort must not be diminished since communities need continuing education and ongoing consciousness raising in order to maximize the ongoing support from (and benefit to) the community for water resource protection and preservation.

If community members ideas are solicited, and the best ones are given some attention and implemented, a community spirit for maximizing beneficial uses of the resource and minimizing its abuse will develop, for the benefit of all. Education and dispersement of important public information can play large roles in bringing about such an ethos.

10.2. Education and training

10.2.1. Aims of water education and training

As stated above one of the aims of any education program in a region of water scarcity must be to develop attitudes to water that will lead the population of the region to sustainably obtain the maximum possible benefits from the limited water resource and to minimize or eliminate wastage of the resource.

10.2.2. Overall water education

Education on water issues is not just needed by the technocrats, managers and operators of water supply schemes. Since everyone in the population uses water and has a vital interest in any supply scheme, educational programs need to be aimed towards the whole population. Everyone has opportunity to misuse water and by undertaking irresponsible activities each inhabitant can have devastating effects on the whole scheme and everyone dependent on it. Everyone in the community needs to be targeted:

- to raise their awareness of water (particularly scarcity) issues,
- to develop attitudes of care and responsibility for water,

- to foster a sense of ownership of the resource,
- to foster protection of the resource and of individuals from water-borne disease by inculcating sensible attitudes to hygiene, washing and separation of wastes from the supply system.

Any educational program needs a many faceted approach and needs to be inclusive of all of the population, with appropriate messages and aims for each part of the population, from the very young to the aged.

10.2.3. Educating children and youths

Children have an involvement with water from the very beginning of life. Drinking and bathing are an important part of their everyday activities. Education and training on water and its importance to every one of us needs to begin long before children start school. Their carers need to be instilling appropriate attitudes to water as early as possible. To do this the carers (usually, but not always, mothers) need to be educated on water issues. The instruction and attitude formation developed around the home needs to be reinforced by the popular entertainment media the children encounter, which may be the village storyteller, children's storybooks, children's radio and television. Books and radio and TV programs are needed which have the specific aim of fostering good attitudes to water. These can take the form of direct instructional material (documentary type) but they must also be supplemented by good attitudes to water being built in to fiction and popular radio and TV series. A huge amount of community attitude formation occurs as people (including children) identify with popular entertainment characters and their activities. Children are very impressionable and open to teaching on all manner of topics. Development of attitudes of care for our vital water resources is a topic to which children's (entertainment) TV could make a large contribution. It is noticeable that in some regions anti smoking campaigns have been greatly assisted by teaching very small children that smoking is unhealthy. Children have an ability to influence the actions of their adult relatives by their innocent questioning of adult behaviour.

Education of very small children on water issues must be a long term strategy and therefore once begun must continue – forever. The benefits of educating the very young on water issues can be that for the rest of their lives these people will be aware of water issues and are likely to be open to consider new thinking on how water can be used more effectively, less wastefully and with less environmental impacts.

Schools. All school curricular should include instruction on water issues appropriate to the region and to the age of the children. In regions of water scarcity the instruction should deal with minimization of water use and protecting water from contamination. Instruction should begin at the school entry level and should continue through all years of school attendance. At secondary school level syllabi could consider innovative ideas on water collection, water treatment, wastewater treatment and water re-use. The need for implementation of some of these ideas will be obvious to children in water scarce regions and the contributions they can make to developing new ideas for conserving water should be fostered and welcomed by their communities.

Tertiary level. Here the focus of water education programs needs to be on environmental issues, policy changes, legal and economic frameworks and details of

technologies. Traditionally water issues have been considered in the engineering faculty but this is very restrictive. As can be seen from the list of issues, above, there is a need to enlist the thinking of all educational disciplines to encourage the broadest possible development of ideas on how to cope with water scarcity. As outlined elsewhere in this book, strategies for coping with water scarcity must not be limited to development of technological solutions, but must involve development of legal systems, the harmonious integration of new water management ideas with local cultural values and therefore needs the attention of many disciplines.

10.2.4. Educating the population in general

Alongside all the direct teaching of educational institutions there is need for ongoing education and reminders for the whole population. Advertising can contribute to this need but it is expensive and not very effective. More important is the introduction of water scarcity issues into popular culture – popular radio and TV series, pop music, cartoons, popular fiction writing, newspapers and popular magazines. In regions of water scarcity the need to reinforce the message of water conservation and protection is so important there should be consideration given to providing government incentives, even subsidies for these activities. Perhaps media that reach a wide audience with water conservation messages could receive favourable taxation treatment.

Households need to be educated to use water sparingly – for showers, bathing, clothes washing and toilet flushing. Similarly outdoor household water use should be confined to keeping vegetation healthy – by irrigating only in the evening. Washing of outdoor surfaces should be minimized and in fact is often unnecessary, a broom can be more effective than a pressurized jet of water.

10.2.5. The role of women

In many regions, particularly those where water is scarce, the role of women is very important:

- women have a large influence in shaping the attitudes of the young, the future majority of the population,
- women often have a large role (with children) in water collection, where there is no direct household supply,
- women largely control in-house water use.

Educational programs of all the types referred above (formal, popular culture, advertising, etc.) are needed which target women. These programs should be aimed at attitude formation and modification.

10.2.6. Farmers and industrial water users

Here there are usually very large opportunities to save water. University courses on irrigation and industrial water use put large emphasis on optimal water use. Unfortunately much less effort is made to transfer these ideas to the individuals who are directly involved in using the water, and these individuals are unlikely to have had any opportunity to participate in University courses. As a result, in many regions of water scarcity the farmers

and industrial water users consume very large quantities of water for quite small productivity. Some of the responsibility for the resulting waste lies with inefficient water laws, water allocation arrangements and water pricing structures. Anecdotal evidence suggests that water supplied free is rarely valued by the user.

There need to be large incentives to encourage farmers to make optimal use of water. Incentives should be made available for farmers adopting water saving and conservation tools, such as for investments relative to purchase equipments for improving the irrigation systems or to adopt conservation tillage. Similarly, financial incentives are appropriate when farmers adopt deficit irrigation or adopt water reuse schemes, or make good use of treated wastewater. Even incentives by themselves are not sufficient. Programs of education for farmers are needed. These need to be run by well trained extension workers who have time to work with the farmers to show them how to make better use of their water. Alongside this dispatch of extension advisers to the farms there need to be well publicized, easily accessible demonstration farms where optimal water use is practiced, where farmers can see for themselves the potential benefits of good water-use practices. Farmers will respond quickly when they see with their own eyes that the returns they could reap for their labour could be increased many times, especially, as will usually be the case, where the physical effort and time required may be no more than for their current practices.

Educational programs for farmers should be well linked with farmer extension programs, including demonstration. In other words, it is a non sense to develop educational programs for farmers and let extension services and extension officers practicing in a traditional way, so often without paying attention to water conservation and water savings. These calls for the need of education of the extension officers and, mainly, to create a new thinking about water issues in extension services.

Similar incentives are needed for industrial water users. Incentives can be in the form of subsidies for purchase of more water-use efficient plant, encouragement of water re-use by removing taxes from recycling plants, by increasing the price of input raw water, or combinations of these. The need is to maximize returns per unit of water, to minimize the unproductive loss of community water and to minimize environmental damage.

Research is needed on how to effectively communicate water saving ideas to farmers, industrial operators and households. In every culture some different approaches will be needed. The aim should be to discover how to raise the consciousness of everyone in the community to the reality that water is scarce and very precious. Everyone in the community needs to be encouraged not just to stop wasting water, but to be looking for ideas on how to get more value from every drop of water.

10.2.7. Managers, operational and maintenance personnel

This is the group that is probably most sensitive to water pricing. As a manager seeks to increase company profits he or she will quickly respond to any large cost item. Few enterprises, except irrigation, really need to consume large volumes of water. Perhaps they have traditionally operated in a particular manner, without recognizing that they were using far more water than was really necessary. Realistic pricing of water quickly attracts managers attention to possibilities for consuming less. In many industries recycling can be achieved at relatively little cost, but even where the cost is higher, the water saved may be

of more value than the cost of purchase and operation of a recycling plant. The initial outlay to develop a recycling system may be high and this is where government funded financial incentives can be effective.

Leakage of precious water is a serious matter in a region of water scarcity. Well motivated maintenance staff can keep leakage and other unproductive losses of water to a minimum. Plumbing staff need to be educated on the value of preventing loss of water by attending to details such as leaking valves, automatic flushing systems which flush more frequently than necessary, leaking delivery pipes, etc.

10.2.8. Educators, agronomists and engineers

An integral part of the education of all teachers, agricultural specialists and engineers should be to instill healthy attitudes to the value of water and the need to optimize the benefits of water use. These professionals have large influence on others who deal with water in their everyday work and so they are in a position to influence water use practices and attitudes to water use. The need is to raise their awareness of the precious nature of water in water scarce regions and to encourage them to pass on these ideas as they go about their professional activities. Bringing the professionals to the point where they take some responsibility for developing beneficial attitudes to scarce water resources should not be taken for granted, or be assumed to be a simple task. Their background, their experience of government activity, their political leaning relative to the incumbent powers, all influence their willingness to assist the community in this way. After their own, or a relative, friend or colleague's bad experience in their job, with an employer or in relations with other agencies, some people are likely to be disaffected and take the attitude "why should I bother?" While this position may be viewed as unprofessional, it is often reality. Therefore programs and leadership are needed to inspire professionals to take leadership roles in promoting sound community attitudes to water scarcity. It is unlikely to occur spontaneously. Effort is required at community leadership levels to inspire others to assist in the development of sound community attitudes to coping with water scarcity.

10.3. Need for new developments and research

10.3.1. New technologies

There are many areas of water resources management where new technologies are needed. Several research agendas in almost all domains of water management for arid and drought prone areas include detailed and excellent ideas to prioritise research, and many efforts are being pursued along such lines. However, for some areas developments are possibly unattainable, for example the need to significantly reduce evaporation from water surfaces. However there are many areas where research could lead to technologies that could make more water available and hence increase the quality of life of large populations. For example can we develop new technologies that will:

- allow increased agricultural and industrial production with less water use?
- prevent the need for disposal of any "waste" water?
- enable desalination of brackish and sea water for costs similar to current costs of

collecting and treating fresh water?

Education lies behind the possibilities for success in these and all other aspects of water saving. Education is needed to bring the whole community to understand water scarcity issues – not just to observe that water is scarce, but to understand why it is scarce. This understanding has the potential to lead to much innovative thinking among the people, on how to reduce waste, how to avoid contamination, how to use less to achieve more.

The best developments will not necessarily be thought up by the water professionals, or even by researchers, but when the whole community is looking for ideas, amazing developments can occur. Not only will the community be contributing ideas but they are likely to be receptive to the need for funding to test the better ideas that are proposed. Testing and developing new ideas usually requires considerable funding and months to years of examination and development of pilot projects to demonstrate the practicality of proposals. To carry such activities through there is a need for widespread community support both in spirit and in resources. Without a solid educational program such support is unlikely to occur and without an ongoing commitment to the educational/public relations effort such innovative, but in many individual cases, ultimately unproductive investigations, are unlikely to be sustained. The supporting community needs to understand that many good ideas, when thoroughly tested, may not produce the benefits expected, but at the same time it needs to continue to solicit and test good ideas.

Research by social scientists is needed on how to develop support in the community for the assignment of resources to investigations of new ideas and approaches to water scarcity issues. Initially enthusiasm may be high but as some avenues of research inevitably produce little of benefit there will be a need to find ways to sustain the community interest and willingness to pay.

In parallel with investigation and development of new technologies there is a need to develop management philosophies that can be used most efficiently to cope with water scarcity within the already existing cultural and traditional environments of the region. Management philosophies need to be developed to:

- encourage the population to understand that the scare water resource belongs to them,
- make the very best use of the available water resource,
- encourage within the population an attitude of care for water,
- encourage innovation and development of ideas and setting up of pilot studies of the most promising ones,
- find means of funding all of the research and development activities.

10.4. Development of public awareness of water scarcity issues

10.4.1. Importance

It is probably that this is really the major educational challenge. History shows it is never possible to bring the whole population to support even the most excellent idea or philosophy.

In order to reach the maximum number of people and to have some chance of

recruiting them to the "cause" of coping well with water scarcity there is a need for a many faceted approach. As a minimum there needs to be very positive leadership at the political level, but also among the opinion makers in the society. All communities have their opinion leaders. In the developed countries these tend to be popular radio or TV show hosts. Sometimes a newspaper columnist can be very influential. In other countries popular TV series, often called "soap operas" can have a huge influence on public opinion. In other areas religious leaders have considerable influence. Advertising and general public information are also important, although these tend to have a more supportive role and are rarely in the forefront of developing community attitudes. However they can be very important in conveying the truth to the people, as truth is not usually obtained reliably from popular entertainment sources.

10.4.2. Media in general

Broadcasters and column writers who have a large popular following can be extremely influential in shaping public opinion and in raising awareness of important issues. In regions of water scarcity an effort is needed to recruit these people, especially the ones who have a large public following, to the need for adoption of strategies for coping with water scarcity. Not only does their interest need to be recruited, but further effort is required to keep them informed of developments and of local needs. These publicists are only likely to give small amounts of on-air time to a particular cause (eg coping with water scarcity) if they are continually reminded of it and if the information they receive is attractively presented and easily assimilated.

Similarly other writers and artists (particularly cartoonists) need to be recruited to the cause. It is important that water scarcity issues become the subject of cartoons, comics and jokes in the community. Authors of these works need to be targeted for special attention concerning coping with water scarcity. Some kind of incentives to discuss "coping with water scarcity", may also need to be provided.

Documentaries for radio, TV and cinemas need to be prepared. While these do not have large public impact they can be very useful in conveying truthful, factual information and providing support to the popular opinion makers.

10.4.3. Advertising

Advertising is probably not very effective, can be very expensive, but it has an important place in getting messages to the public. It provides an opportunity to make sure scientifically correct information is circulated. Advertising cannot be done "on the cheap". It is expensive, and needs to be put in the hands of a successful, culturally aware advertising agency which can attract public attention. Paid advertising can really only draw attention to an idea. It cannot provide all the information needed to shape public opinion. However it should be an important part of the overall "awareness arousing" strategy.

In locations to which electronic media do not reach and where education levels are not high there may be a need to have a small team of "information providers" visit on a regular basis – perhaps 3 monthly – to raise awareness. This may need to be undertaken in a variety of ways including street theater, fun visits to schools, public meetings (unlikely to be well attended), free public film shows and even high density use of posters.

10.4.4. General public information

Usually, provision of information important for life is considered a government responsibility. All the activities discussed above could be considered to be public education, also a government responsibility. There is a need to initiate and sustain a campaign to raise public awareness that coping with water scarcity is a responsibility of every member of the population. We all desire to continue living, and water is needed for life. Given some commitment and determination it should not be too difficult to obtain funding and assemble a group of dedicated, determined people to promote attitudes of care for water in the community. The group is needed to coordinate activities and particularly to recruit opinion makers to the cause. They need to be free to use all possible means to achieve their aims. They need to devise approaches that fit in with the local culture, customs and even current fashions. If there is no tradition of reading newspapers, or if many in the population are illiterate then written messages or advertising will have little effect. If TV or radio are not available or have little appeal then these media will similarly not provide a means of shaping opinions. The existing local communication systems should be used, and if these are not appropriate for transmitting opinion changing material on coping with water scarcity the group may need to devise some new form of communication method (a considerable challenge!). This may seem an extreme proposal, but we need to remember the issue is survival! If communities do not learn to cope with water scarcity in an adequate, locally appropriate and equitable, sustainable manner they will go out of existence!

Therefore there is a need to find ways to capture and retain, in the long term, public interest in, and willingness to contribute to finding ways to cope with water scarcity.

10.5. Conclusion

Education to develop routine attitudes to coping with water scarcity is needed at all levels of society. Commitment is required of the local community to encourage the development and ongoing promotion of education about coping with water scarcity to the whole community. Commitment is stressed because to sustain beneficial attitudes to water the educational programs must be continuous, not just one-off or short term activities. Commitment is also needed to provide the funding needed to support ongoing programs. Educational activities need to be aimed at all levels of the community and therefore a single activity cannot be successful. Education will not be successful if it is only conducted in the classroom. It must be integrated into all forms of popular culture and entertainment and become the responsibility of every member of the community.

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