Modern and Traditional Irrigation Technologies in the Eastern Mediterranean

edited by Özay Mehmet and Hasan Ali Biçak

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INTRODUCTION

Özay Mehmet and Hasan Ali Biçak

A water crisis is threatening several regions of the world, most notably the Middle East and North Africa. The papers presented in this volume discuss this crisis from a multidisciplinary perspective and focus specifically on the role of modern and traditional irrigation technologies in the response to this growing water crisis. The papers were originally prepared for the 2nd Regional Workshop on Water Resource Management, held on 2–4 April 2000, at the Eastern Mediterranean University (EMU) in northern Cyprus. The workshop was hosted by the EMU and sponsored jointly by the International Development Research Centre (IDRC), of Canada, and the Ministry of Agriculture and Forestry of the Turkish Republic of Northern Cyprus (TRNC).[1] The present volume is a sequel to an earlier one published by the IDRC, based on the workshop in Ottawa in October 1997.[2]

A key objective of the EMU workshop was to generate information on modern, as well as traditional, irrigation methods in agriculture in the eastern Mediterranean. To this end, the workshop included several case studies and field reports from several countries dealing with irrigation and wastewater reuse and conservation technologies. Like the workshop in Ottawa, the EMU workshop was multidisciplinary, enabling crossfertilization of ideas and research findings from the disciplines of economics, hydrology, agronomics, engineering, and environmental studies.

Water-demand management

Following the opening ceremony, chaired by the Hon. Minister of Agriculture and Forestry of TRNC, the workshop began with a keynote paper from Prof. Hamdy, who discussed the challenge facing water planners and managers at the end of the

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[1] We would like to express our personal thanks to all the sponsoring organizations for their generous support of this workshop. In addition, we would like to acknowledge the contributions of several graduate students and support staff at the EMU for local arrangements.

[2] David B. Brooks and Özay Mehmet, ed. 2000. Water balances in the eastern Mediterranean. IDRC, Ottawa, ON, Canada.

20th century, both globally and regionally in the Mediterranean. He argued that although the physical availability of water to each country is constant, demand for water will continue to increase steadily for the foreseeable future. Accordingly, the challenge will be to find a way to balance demand and supply of water under these difficult conditions.

Some of the factors contributing to the water crises are population trends, including explosive urban growth, mismanagement of water resources, structural imbalance between water demand and available water resources, and limited information on water resources. In fighting the water crisis, an effective water management is a must, but one also has to consider the following challenges: principles of agricultural water-demand management, the role of economic incentives, water-pricing and cost-recovery, improvement of technologies, both for irrigation and water conservation, and methods to optimize water for crops, irrigation scheduling, and reallocation of irrigation water to low water-consuming, high-value crops.

While adopting a water-demand management strategy to solve the water crises one could also investigate the uses and losses of water in the drinking-water, industrial, and agricultural sectors. The reduction of transport losses in the irrigation sector by 50% and the improvement of the irrigation efficiency from 45 to 80% could provide water savings of nearly 52 000 m^3 of water a year, giving an additional supply of nearly 20% of actual demand for water.

One of the most important observations in Prof. Hamdy's paper is the dramatic contrast between water use in Europe and in the Mediterranean region and the critical role of agriculture in this contrast. Wasteful use of water in agriculture in the eastern Mediterranean prevails in the still-extensive traditional flooding system of irrigation. However, farmers are gradually adopting modern technologies, in particular drip irrigation. But these new technologies require heavy capital investments and operational outlays, often beyond the means of individual farmers.

Drip Irrigation

Following the keynote presentation, Prof. Osman Tekinel, the eminent Turkish agriculturalist, and Riza Kanber presented a paper. They presented findings on a series of extensive experiments in Turkey with drip irrigation, involving a variety of soils, crops, and climatic conditions. Tekinel and his team reported uniformly increased efficiency in water use, as a result of drip irrigation. They showed that drip irrigation realized the highest yield with good quality from all plants and with less water.

Some variance occurred in this overall result for a variety of crops in various regions of Turkey. Thus, the yield of tomato grown under drip irrigation in greenhouses varied with planting time. Spring planting gave the highest yield. Drip irrigation generated water savings in 25-year-old orange and lemon orchards. However, the experiment showed no increase in yield from irrigation methods. With commercial use of drip irrigation yield increased 27%, and the discarded yield decreased 5% over other methods. Using drip irrigation saved 50% of irrigation water in banana cultivation. However, the study saw no increase in the yield from irrigation methods. Cotton has received drip irrigation for the last decade in the Lower Seyhan Plain of Çukurova, the Harran Plain in the Güneydoğu Anadolu Projesi (GAP, Southeastern Anatolia Development Project) area, and the Aegean region. It has increased the cotton yield 34% over furrow irrigation in the Harran Plain. Although no statistical difference appeared between irrigation methods (namely drip, sprinkler, and surface methods), in Çukurova drip irrigation achieved water savings of 54% and a decrease in yield of 3% over the pounded-furrow method.

The water problem in northern Cyprus

The next two papers in the volume discussed the water problem in northern Cyprus. Prof. Korukcu and his team report on drip irrigation technology in a pilot project in northern Cyprus, where 9059 ha (48%) out of 187 069 ha is irrigated. The major part of irrigated land is in citrus areas (6363 ha, 70.24%), and 84% of these are in Güzelyurt region (about 5344 ha). Groundwater resources are the main sources of water for irrigation in northern Cyprus, mostly located in the Güzelyurt region. Traditionally, farmers have used the flooding method to irrigate citrus trees in this region. Until 1997, only about 25 ha of citrus orchards had drip irrigation systems, or a small fraction of the total area under citrus cultivation. Since then a pilot project has expanded drip irrigation to a 1400-ha area in the region.

Saline-water intrusion from the sea was the subject of Dr Ergil's paper. Contamination of coastal aquifers from seawater has a variety of causes, such as pumping in excess of their safe yield capacities or farmers' overpumping near the shores, or both. The calculation of the amount of continuous water use within the aquifer is made using a volumetric (3-d) approach in both water- and salt-balance equations, with integration of space and time components. Using a variety of technical assumptions and estimating techniques, Dr Ergil projected the total amount of remaining freshwater available within the Güzelyurt aquifer at 1565 Mm^3, and the remaining life of the aquifer would be less than 50 years at the current levels of use.

Integrated agricultural management

Dr Al-Zabet's paper on water use in Jordan focused on water-supply infrastructure and land-reclamation works in the Jordan Valley. It studied integrated agricultural management using telescopic-refinement methodology to optimize the land use with maximum water-value return. For the purpose of this study, the Jordan Valley was divided into four zones to investigate sound agricultural practices in each zone, taking into consideration the integration of agricultural zones.

The study showed that in zone 1 (North Shounah), which has an abundance of water, coupled with good-quality soil, the land is most ideal for farming fruit trees and vegetables. Zone 2 (Deir-Alla) is most promising for vegetable farming. Zone 3 (South Shounah), which has poor soil and limited water resources, should have only greenhouse agriculture. In zone 4 (Ghor Al-Safi), the study found that agricultural development depends on the availability of surface water, which in turn depends on having new dams on the side-wades.

The Jordan Valley has suffered several related constraints on agricultural productivity. It has needed research to develop new crops with promise of higher rates of return, lower water consumption, and better disease resistance. As well, it has needed an innovative marketing system to balance supply and demand for crops to ensure orderly marketing opportunities for farmers, rather than promoting commercialized mass production. Finally, efficient water allocation would be essential for achieving water savings, so as to divert part of them to other vital sectors, such as municipal households and industry.

Supply and demand management

As Dr Amery's paper showed, Lebanon has more water than its neighbours. Dr Amery's presentation outlined the evolution of irrigation in Lebanon and evaluated the ecological, economic, and domestic geopolitical consequences of dam-building. He critically assessed the policy of concentrating on dams to expand the country's water resources. An essential element of this policy has been the government's belief that the country would face a water crisis unless it constructed a large number of dams. As a result, it has regarded dam construction as the way to meet the water requirements of Lebanese farmers and urban residents alike, without a commensurate concern for water conservation through, for example, modern irrigation technologies and more efficient pricing of water. This is especially valid now, after the civil war.

The Southeastern Anatolia Development Project: irrigation unions

The next two papers focused on the Turkish megaproject, GAP. This region is economically the poorest in the country but is richest in water resources, containing as it does the waters of the Tigris and Euphrates rivers, which cross this region on their way to Iraq and Syria. As a result, these waters have been the subject of much dispute between Turkey and its Arab neighbours. Notwithstanding, the Turkish government has invested heavily in GAP.

Mr Alemdaroğlu's presentation on GAP emphasized that irrigated agriculture is the foundation for sustainable development of the GAP region. Since 1992 the Project on the Management-Operation-Maintenance (MOM) of GAP Irrigation Systems has provided a model for the GAP region. The major objective of the MOM model is to provide an institutional and organizational framework to maximize net benefits from irrigated agriculture in the GAP region and ensure its financial and physical sustainability. The MOM model encompasses a network of irrigation unions to promote integrated and sustained irrigation-system development in GAP.

The Southeastern Anatolia Development Project: irrigation methods

In a related paper on GAP, Dr Kibaroğlu also discussed MOM. Within this framework, she devoted a significant part of her paper to a discussion of alternative irrigation methods being tested on 3131 ha in the Şanlıurfa Plain to compare their water savings, including the classic canalette (flumes) network, low-pressure irrigation, and pressurized irrigation. The soil and topographical characteristics of the pilot area were average for GAP irrigation schemes. The technical solutions developed for the pilot zone had been, therefore, applied to other schemes in the region. Through this implementation in the pilot zone, technical, economic, and operational merits of various water-management practices were studied in the actual farmers' environment.

In Turkey, gravity-driven irrigation, through standard canalette networks, is the most extensively used irrigation method for large schemes ranging from several thousands to several tens of thousands of hectares. However, in line with the interim results obtained in the pilot-project area, State Hydraulic Works (SHW, Turkish acronym) has started to build a low-pressure irrigation network through buried pipes with downstream control, in about 125 000 ha of the GAP region. This is the government agency responsible for, among other things, the design and construction of irrigation facilities. When irrigation projects in GAP are fully realized, 35% of the irrigation areas in the region could be under pressurized-pipe irrigation. Moreover, to obtain the possible advantages of widespread pressurized system in the whole GAP region, SHW has started to implement low-pressure "California" irrigation systems in the schemes under construction. Low-pressure pipe-irrigation is technically feasible in the GAP region. Systems using low-pressure buried pipes have water conveyance and distribution efficiencies as high as 90%, compared with 50–60% for earthen canals. Low-pressure buried-pipe systems prevent losses from seepage and evaporation.

Wastewater irrigation with minimal health risks

The EMU workshop was also notable for its emphasis on water-conservation and recycling options, with minimal health risks. The final paper was a presentation from Israel and was particularly significant, as it reported on cutting-edge technologies in this field.

Prof. Oron's paper described an integrative research project in progress on optimal wastewater treatment, disposal, and reuse with minimal environmental and health risks. The study has used secondary domestic wastewater in conventional on-surface drip irrigation and advanced subsurface drip irrigation (SDI) systems to irrigate various crops. Under SDI, the soil performs as a complementary biofilter for the conventional treatment of domestic wastewater.

Prof. Oron's paper cited some interesting field results, to date, showing improved yields under SDI. In addition to favourable results in physical production, this irrigation method diminishes the health and environmental risks, as it minimizes contact with the disposed effluent in on-surface agrotechnological activities. Furthermore, the field results indicated no direct contact between the above-surface foliage of the plants and fruits and the effluent. Nor were there any specific problems of emitters clogging, thanks to adequate filtering of the effluent.

Summary

The international gathering of scientists and researchers at the EMU workshop highlighted some of the latest research findings in water-resource management in the countries of the eastern Mediterranean. As editors, we feel gratified to have had this wonderful experience and thank all contributors for sharing their valuable findings with the wider community of policymakers and researchers. Needless to say, the work is by no means complete. Our earnest hope is that this small volume will be followed by subsequent contributions on issues in water cooperation and management in the eastern Mediterranean, clearly one of the most water-stressed regions of the world today. At this workshop, the participants agreed that the focus of a workshop at the regional headquarters of GAP in Şanlıurfa, Turkey, should be the social-capital and human dimensions of irrigation and regional development projects in the eastern Mediterranean.

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Chapter 1

Water-Demand Management in the Mediterranean

Atef Hamdy

Introduction

Current trends indicate an approaching water crisis in several regions, most notably the Middle East and North Africa, but also in an increasingly large number of countries worldwide. In the near future, the main constraint to agricultural development of arid and semi-arid land in the Mediterranean will be the availability of water, rather than land. Most countries in the region with erratic rainfall patterns have already developed or are developing many of their economically usable available water sources. Without efficient control and proper water management, most of those countries will find that self-sufficiency in food and energy remains a mirage.

Although the physical availability of water to each country remains constant, the demand for it will increase steadily for the foreseeable future. The major challenge facing water planners and managers at the end of 20th century will be to balance demand and supply of water under these difficult conditions.

An efficient and environmentally sound management of the available water resources in each country is really the only solution. The region needs feasible and realistic water management strategies to deal with the following issues:

- Safeguarding water to meet basic needs for various uses;
- Minimizing water losses;
- Allocating scarce water for socioeconomic development; and
- Protecting the environment from degradation and loss of productive capacity.

At the moment, the policies, institutions and planning procedures in place to manage water are not well suited to these tasks. A flurry of international activity in recent years has called attention to the problem of water scarcity and the need for action to solve it. Agenda 21, the global action plan that emerged from the 1992 Earth Summit in Rio de Janeiro, and the World Bank's 1993 water-resources policy paper put forth helpful guiding principles and spawned a variety of national studies.

The United Nations Commission on Sustainable Development requested a global freshwater assessment, which is now under way, and the study team reported to the United Nations General Assembly in 1997. Most nations have not realistically assessed how limited water supplies will affect their food production and economic prospects. They need to set priorities and make trade-offs.

One of the lessons learned over the past decade is that technical solutions alone cannot provide the increasing population of the region with safe water supply and proper environmental sanitation. The region needs to integrate the technical, institutional, managerial, social, and economic aspects of water-resources management. The new approach for sustainable water supply and sanitation depends on local involvement, solutions, and knowledge within an overall framework of water and natural resources planning.

The future requires new mechanisms to protect the region's water resources and allocate diminishing supplies for increasing and competing uses. Anticipatory and preventive approaches would help in managing the quality and quantity of water in arid regions while acknowledging its social, economic, and environmental aspects.

The Mediterranean needs a new ethic, one that promotes efficiency and protection of the water system in everything people do. Efficiency must be the option of first choice. Part of that ethic would be to accept the obligations accompanying the right to water, obligations to protect its many ecological functions, get as much as possible out of each litre we take of it from its natural course, and help others to receive its benefits.

The Mediterranean water crisis

This section reviews the most important of the many interrelated factors contributing to the Mediterranean water crisis.

Limited information on water resources

A basic problem in the Mediterranean and in many regions of the world is inadequate knowledge of both the resources and the demand for water. It is thus essential to know not only the average values but also the spatial and temporal distributions of stochastic variables controlling the supply of water in the region.

Collection, processing, and analysis of good-quality data on the quantity and quality of surface water and groundwater resources are vital in planning to meet water demands. The quantities of water available to communities in dry lands and the safe output from the aquifers are key factors in long-term sustainable development and the war on desertification. Equally important is information on water, particularly data on water abstraction and consumption for various purposes, as well as data on wastewater discharge. Researchers must intensify their efforts to gather, organize appropriately, and disseminate fundamental water data.

Data management is a main issue and the essential one in reliably predicting water supplies and formulating allocation strategies.

Population trends and explosive urban growth

The total population of Mediterranean countries is around 360 million (Figure 1), but will reach between 520 and 570 million in 2025. The difference between the two numbers is equivalent to the current combined population of Egypt and Turkey. Countries north of the Mediterranean basin, from Spain to Greece, will account for only about one-third of the total population in 2025, compared with two-thirds in 1950 and about one-half today. In contrast, the countries south and east of the basin, from Morocco to Turkey, will comprise nearly two-thirds of the total basin population in 2025, that is, twice their current number and nearly five times that in 1950.

The rate of this high population growth is an average of 3% yearly in southern countries, and this alone can be expected to increase the total water requirements. However, past experience indicates that per capita water requirements also increases with standards of living.

Rapid population growth is always linked to fast urbanization (Figure 2). Urban growth will be explosive in the southern and eastern countries, where it has been, on average, five times faster than in 19th-century Europe. Growth rate is not the only factor to consider. Urban populations will be very large: 200 million more inhabitants in 2025 in the areas south and east of the basin, that is, as much as the total urban population of the Mediterranean region at present. The urban population of the Mediterranean basin could, in fact, number between 380 and 440 million, compared with a little more than 200 million today. Although the annual growth rate of urbanization is high in the Mediterranean region in general, it is much higher in the south of the region (4.5%) than in the north (2.8%).

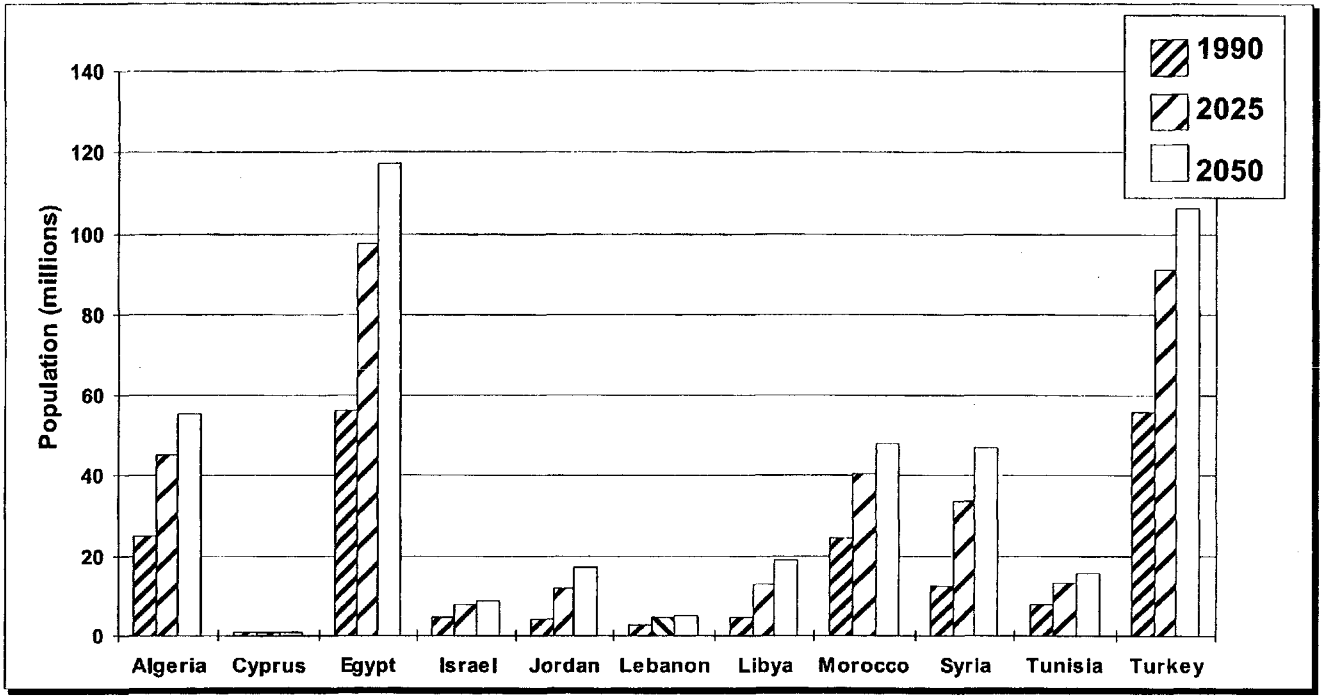


Figure 1. Population growth in southern Mediterranean countries, 1990–2050. Source: UN–PD (1994).

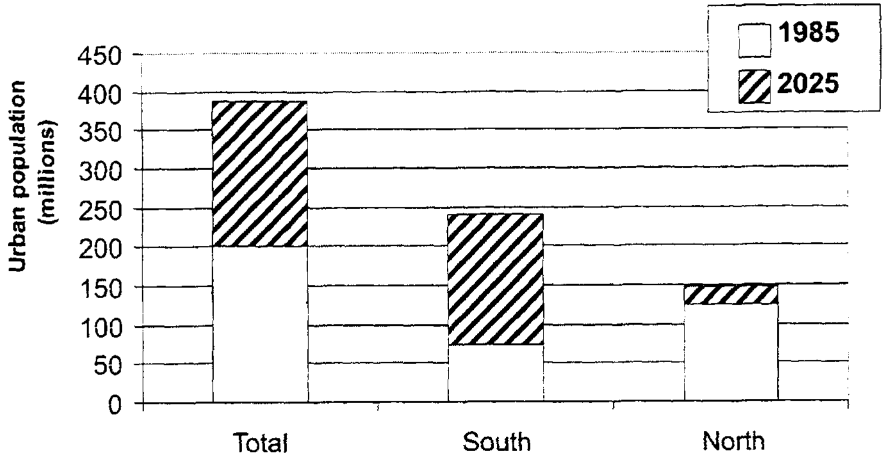


Figure 2. Urbanization growth in the Mediterranean, 1985–2025. Source: Grenon and Batisse (1989).

Under such conditions, southern and eastern Mediterranean countries will find it difficult to be self-sufficient in meeting their needs for agricultural, domestic, and industrial water. One of the most critical challenges will be to supply drinking water to urban areas.

Water scarcity

Water scarcity will be the main problem for future generations and have effects in many parts of the world. Water scarcity is a great threat to the global sustainability of the water supply and potentially to world peace and development. The scarcity will affect mostly the poor (especially women and children) and will undermine the economic, social, and environmental foundations of many developing countries. Water scarcity leads to the deterioration of water quality. And usable freshwater resources are finite, adding to the fragility of the global system.

In the southern arid and semi-arid countries of the Mediterranean, water is scarce, often of poor quality, and vulnerable to pollution, sometimes a nonrenewable resource, and harmful to the soil. Flooding can have devastating effects in these countries.

Countries in the Mediterranean as a whole use 72% of their water resources for irrigation, 10% for drinking, and 16% for industry. But northern Mediterranean countries make completely different uses of water than in the south (Figure 3).

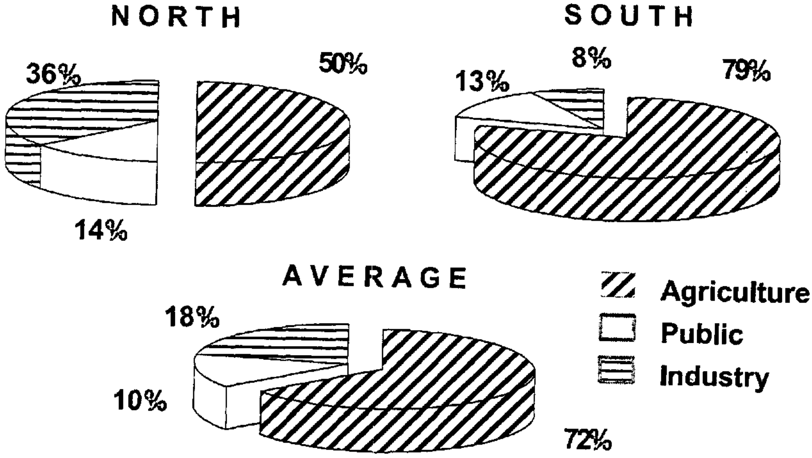


Figure 3. Water use in Mediterranean countries. Source: Elaboration on LAMBED World Resource Institute data, 1985 (WRI–IIED 1985).

Other pressures on demand further complicate the overall picture. Summer tourism on the coast can double or triple water use and lead to crisis situations. Another important factor is the presence of industries that are large consumers of water (for example, power stations and pulp factories). The development of urban centres around the basin means that the water supply can break down when drought persists. Per capita availability of water (Figure 4) is the true measure of water scarcity in the region.

Mismanagement of water resources

Despite differences between the arid and semi-arid Mediterranean countries in their societies, political systems, cultures, and economies, they are similar in many ways, such as the following:

- Poor management practices, inefficient water use, and failure to place a high economic value on water, which result in resource degradation from water logging, soil and water salinization, and pollution of aquifers;
- Few incentives for water conservation in agriculture and numerous disincentives;

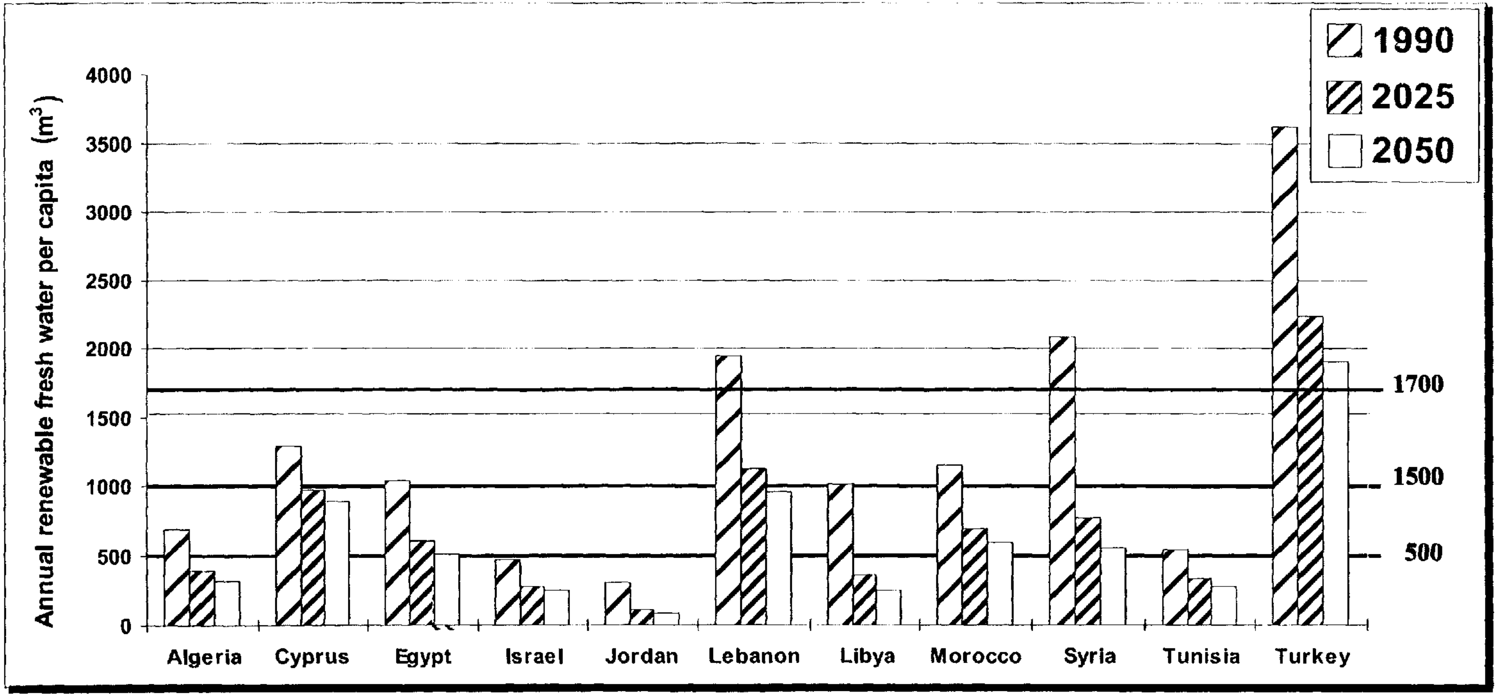


Figure 4. Available fresh water per capita in southern Mediterranean countries, 1990–2050. Note: 1700 m^3 = periodic water stress; 1000 m^3 = chronic water stress; 500 m^3 = absolute water stress. Source: UN–PD (1994).

- Irrigation developing faster than water-source mobilization (population growth and increasing demand for water for other uses are leading to rapid mining of aquifers, water shortages, competition, and conflict); and

- Questionable outlook for developing new water supplies to meet increasing demands, given limited financial resources, escalating construction costs, and rising environmental opposition.

Average losses of irrigation water in the Mediterranean are extremely high (55%), and they are distributed among farm distribution (15%), field application (25%), and irrigation-system losses (15%). Only about 45% of water diverted or extracted for irrigation actually reaches the crops. Losses vary widely, with those from the conveyance system varying between 5 and 50%.

Such low efficiencies in agricultural water use and the unsatisfactory features of irrigated agriculture in the region's developing countries are undoubtedly the result of the mismanagement of the water resource.

Water-policy overlaps

A major institutional constraint in all developed and developing countries is the sectorial approach to water development. This has an important bearing on the projects sustainability. Water-resources management is typically divided among a number of governmental sectors. This means that water policies are not the exclusive domain of a water-resources sector but overlap with other sectorial policies, as illustrated in Figure 5. In addition, national macroeconomic policies on finance, budgets, and trade can have important impacts on water-resources management.

To formulate and set up an overall national water policy, countries in the region will need to analyze the links between water and other economic sectors, including agriculture, industry, transport, energy, and health, and this will entail having policies on

- Water-resources sector as a whole;

- Specific water-resources subsectors, such as potable water and irrigation; and

- Other sectors affecting water resources, such as energy.

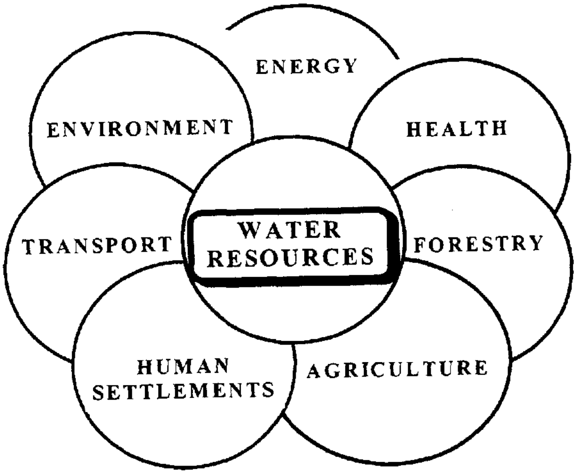


Figure 5. Water-policy overlaps. Source: Hamdy and Lacirignola (1999).

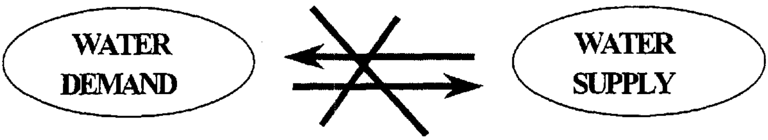
Structural imbalance

Strongly evident over the next few decades will be the structural imbalance between a constantly increasing demand for water and the naturally available water resources (Figure 6).

Over the last few decades, the imbalance only affected a few countries, and the gradual additional harnessing of natural resources wrongly thought of as being infinite, met the requirements. The room to manoeuvre is progressively contracting, and fewer and fewer of these resources will be available in the future.

In several Mediterranean countries, an imbalance will have started to appear around 2000. The water demands of southern Mediterranean countries will have fast approached resource limits, and the majority of these countries may have entered into a period of chronic shortage during the 1990s. These countries will be facing several similar problems, outlined as follows:

- Declining water resources per inhabitant, both in terms of availability and withdrawals (available water per capita will fall by nearly 50%);
- Exploitation of water at a fairly high rate, with the risk of water-quality deterioration;



Steadily increasing **No existing balance** **Fixed and limited**

How to balance the water equation?

Water savings
- **Improvement of efficiencies and water conservation**
- **Reallocation of water supply**
- **Economic incentives**
- **Water control and prevention of losses**

Reuse of new water resources
- **Treated municipal water**
- **Saline water**
- **Recycling of waste water**
- **Conjunctive use of surface and groundwater sources**

Increasing the supply is marginal
- **Most accessible water resources have been developed**
- **Investments are currently shrinking**
- **Cost of less accessible water will be high, and the process is time consuming**
- **The environmental and human costs of project are enormous**
- **Very little can be done**

Figure 6. Water-resources dilemma in the Mediterranean region. Source: Hamdy and Lacirignola (1999).

- Excessive reduction in water withdrawals per capita will significantly impact water use, creating notable competition and conflict between users in various sectors, especially in the irrigation and domestic sectors (countries will give priority to satisfying the demand for drinking water over that for irrigation and see less irrigated land and more land degradation, as a result); and

- Progressive degradation in the quality of available water resources, owing to increasing discharge of waste into water bodies and the atmosphere.

This context of structural imbalance suggests the question of whether we need a new management approach to overcome conflicts between water users and attain sustainable sectorial water use? One can easily answer this question through an analysis of the management approaches in the developing countries of the region.

Those approaches are physically, economically, or environmentally unsuitable:

- Water misallocation occurs, with low-value uses consuming a significant share of the resource and high-value uses suffering shortages;
- Water quality is left unmonitored, leading to inappropriate use of low-quality water;
- Water and sewage services are inadequate, especially for the poor; and
- Costs of new water development are mounting.

The region cannot resolve these issues using the current fragmented approach. The dilemma to sustainably produce more with less water, points to the need for water-demand management. This should review water uses and the various tools to promote more desirable levels and patterns of use. It should incorporate aspects of conservation and efficient use, essential to achieving a reasonable balance between demand and supply.

Countries in the region should concentrate water-demand management on the agricultural sector, as irrigation takes the highest share (80%) of water use, and the agricultural sector could supply most of the water savings needed to meet the growing water demand in the municipal and industrial sectors. Water-demand management of irrigated agriculture would be the bedrock of sustainable water use in the region.

Issues in water-demand management

Water problems and management

The problem of water resources and efficient management is at the heart of the common concerns of the Mediterranean countries, today.

Chapter XVIII of Agenda MED 21, the Mediterranean version of Agenda 21 adopted by the United Nations Conference on Environment and Development, emphasizes that all Mediterranean countries should have prospective studies, "to anticipate medium and long-term development in countries already facing sharp water shortages and recommended solutions likely to reduce their effects" (United Nations 1992, p. 170). Mediterranean Action Plan phase II, by broadening its objectives within the framework of the revised Barcelona Convention, adopted in 1995, included among its priorities the management of water resources for sustainable use.

The creation of the Mediterranean Commission on Sustainable Development (MCSD), in 1996, underlined the political determination of the region's governments, the European Union, and various public and private partners to develop regional and subregional cooperation. These actors are the most appropriate to promote the incorporation of environmental concerns into development policies.

Water management becomes the core of sustainable development after water extraction reaches about the same level as resources, and MCSD rightly included water-demand management as one of its short-term priorities for 1997.

Attenuation or adaptation of water demand can help supply meet demand to a large extent. The awareness of this fact makes water-demand management a very topical issue, and the following therefore briefly summarizes the objectives, methods, and means of adoption of water-demand management.

Objectives

Water-demand management has four major goals:

- Conserving rare or costly resources;
- Minimizing the cost and effort of providing water;
- Limiting disputes over use; and
- Making the best use of water.

Water-demand management thus seeks to reduce both nonuse of available water and its misuse, such as through system defects (loss, leaks, lack of efficiency), unnecessary or superfluous use, excessive use of high-quality water where lower quality water would suffice, badly chosen use and reuse, defects downstream of use. Objectives of water-demand management are therefore as follows:

- To reduce demand or, at least, slow down its increase;
- To safeguard future generations' right to water;
- To ensure equitable water distribution;

- To alter factors governing water requirements and adapt the sectoral structure of water use to promote the most effective use;
- To maximize the socioeconomic output of the unit volume of water and thereby increase water-use efficiency; and
- To coordinate and maximize multiple uses of the same water.

Methods

To achieve these objectives, the region must take action on three levels:

- Water conservation (which is the responsibility of agents, distributors, and users);
- Organization of collective water use to promote, in particular, sequential use (reuse); and
- Allocation of resources among sectors (according to socioeconomic and political criteria).

The demand-oriented measures include an array of instruments, technical (water conservation, cropping), economic (subsidies, tax and price policy, water tariffs), administrative (licences, regulations, policing, capacity-building), legal (water law, water rights, fines), operational, and political. They will be different for each country, depending on its physical characteristics, administrative system, and cultural environment.

Although these instruments will all have the same purpose, strategies will vary greatly, according to each country's situation and expected future development. The choice of solution and implementation of management tools will depend to a large extent on the major types of defect, level of imbalance between supply and demand, and the socioeconomic situation of each country.

Why water-demand management for irrigated agriculture?

Countries of the region that irrigated agriculture will first and disproportionably be affected by increasing water scarcity and growing demand from other sectors. Agriculture will indeed have to compete with higher value uses if market mechanisms have free play. The World Bank concluded that the high opportunity cost of water and the lack of economic opportunities to increase supply on a large scale will result in agriculture releasing freshwater resources to other sectors over the long term. Most of the water savings needed to meet growing municipal and industrial water demand would have to come from the agricultural sector, not only because irrigation takes the highest share of total water but also because it has considerable potential for efficiency improvement. In typical traditional irrigation schemes, as little as 30% of applied water may be used for crop evapotranspiration. Modern schemes — and there are examples of this within the region — can achieve project efficiencies of about 65%. Assuming a typical situation, where 80% of total water use goes to agriculture, a 10% increase in the efficiency of irrigation would provide 50% more water for municipal and industrial use. This is a good illustration of the potential for water savings in agriculture and helps to explain the need to press for it.

Contrary to much of what is said in the popular literature, agriculture will not necessarily die if it receives less water. Microirrigation, for instance, can save about 30–50% of water on the farm and, together with better agronomic and culture practices, can double or treble yields per unit of water. Modernizing agriculture can stimulate an array of associated economic activities, such as agro-processing and manufacturing of irrigation pipes and equipment. Much of this activity would occur in the private sector, which often has the needed access to international expertise and technology.

Guiding principles of agricultural water-demand management

Agricultural water-demand management relies on more efficient use of water, changes in agricultural production practices, and reduction of waste.

Adequate water-demand management in the agriculture sector requires structural incentives, regulations, and restrictions to help, guide, influence, and co-ordinate farmers' efforts in making efficient use of water and encourage their adoption of innovative water-saving technologies.

Agricultural water-demand management should have the achievement of the following as its guiding principles:

- Interaction of the quantitative, qualitative, and biological aspects of both ground- and surface water;
- Sustainability of irrigation and drainage schemes;
- Better water savings and reduced irrigation losses;

- Environmental sustainability;
- Improved economic return on irrigation;
- Institutional and human-resources capacity-building for the execution of management tasks; and
- Certain aspects of implementation, such as financing, monitoring, and control; farmer's participation; consideration of social and cultural issues; and technical facets of water use.

To achieve efficiency and equity, a program of agricultural water-demand management would require development particularly in the following aspects:

- Economic incentives; and
- Irrigation efficiencies and water conservation.

Economic incentives for improving irrigation water-demand management

WATER PRICING AND COST RECOVERY — Economic incentives based on cost recovery of irrigation water supply may play a major role in encouraging farmers to save irrigation water. In the southern Mediterranean countries, irrigation water is either free or costs less than the full cost of providing irrigation services. Most irrigation projects are subsidized to support agricultural production. But recent budget constraints and increasing water scarcity and demand have led some countries to reduce such subsidies to make irrigation schemes responsible for generating enough revenue for their operation and maintenance (O&M), reduce the burden on the government budget, and create incentives for farmers to invest in water-saving irrigation technologies and move away from crops with high water requirements.

Irrigation charges are a very important prerequisite to good management because current irrigation management practices allow widespread misuse of water in agriculture, despite water shortages. This has been mainly due to a failure to recognize the economic value of water and the real cost of water services. Therefore, many economists now believe that managing water as an economic good is important to achieving efficient and equitable use of water, as well as to encouraging the conservation and protection of scarce water resources. Yet, many states in the region find it difficult to reconcile this concept of water with the traditional idea of it as a basic necessity to which everyone should have the right of free access.

WATER-PRICING CONCEPT AND CRITERIA — Water pricing is a sensitive issue, but could be an effective instrument, if properly understood and applied. Principle 4 of the Dublin Conference states that "Water has an economic value in all its competing uses and should be recognized as an economic good" (ICWE 1992, p. 4).

The true economic value of water comprises two components, namely, the value of the resource per se, as a utility or input to production, and the cost of service, meaning the cost of development and supply. Water-pricing policy analysis should take these components into consideration. However, the price to the consumer need not include the full cost, depending on social, political, and cultural considerations.

The fundamental role of water pricing is to help determine the allocation of a limited resource between competing uses and users, implying both efficiency and equity objectives. In practice, market forces seldom set prices for agricultural or rural water supply, which is usually the task of a public utility or regulated private water company. Whether based on a flat rate, marginal costs, average costs, or the ability to pay, each charging system has implications for allocative efficiency, equity, and fairness in apportioning costs.

The following considerations for arid and semi-arid countries of the Mediterranean are the most obvious reasons for thinking irrigation-water pricing an important issue and could affect our understanding of it (Biswas 1991):

- Water allocation between competing uses;
- Water conservation;
- Generation of additional revenue to operate systems and repay investment costs;
- Cropping patterns;
- Income distribution;
- Efficiency of water management; and
- Overall environmental impacts.

Although water pricing will unquestionably be an important policy instrument in the 21st century, the criteria for setting prices are still a major issue. Should the beneficiaries pay the O&M costs of the water system? Or are they expected to pay total investment costs as well? Should such pricing include external costs, such as environmental and social damages? If so, how should these costs be calculated? We will have to find answers to these difficult issues.

Local governments are under pressure to implement cost-sharing schemes to expand irrigation. Conflicts are already occurring between government and private sector in agriculture. Decisions based on insufficient information and background may produce negative impacts, the opposite of those needed to increase water efficiency and productivity. Policy- and decision-makers must improve their understanding of the characteristics and motivations of the human components of the irrigation system.

A number of factors should influence the selection of pricing mechanisms for the various countries of the region, such as sectorial use, levels of subsidies, irrigation-water conservation, ability to pay, and rural social welfare. The dual objectives of generating income and encouraging efficient use of irrigation water through cost recovery would inevitably require innovative approaches and strong farmer participation.

Irrigation efficiencies and water conservation

Water conservation and efficient water use have not received the attention they deserve in many parts of the Mediterranean. However, as agriculture is by far the largest water user, efficient irrigation management will undoubtedly be a major conservation option in the future.

At present, it is fairly common to find that more than half of the water drawn from a resource never reaches the field. In general, only about 25–30% of the water diverted into large canal systems in developing countries actually becomes available to the crop, an efficiency of less than 40%.

One of the factors contributing to such inefficient water use is the emphasis on constructing new supply facilities, rather than improving the efficiency of existing ones. Countries in the region may pursue opportunities to improve irrigation water-demand management through better farm water management systems, which should include reducing distribution losses, changing cropping patterns, improving scheduling, and adopting more efficient technologies.

The major causes of the current low irrigation efficiencies are factors such as leakage, percolation, and evaporation. Very often these factors are due to deterioration resulting from inadequate maintenance of the irrigation network. In such cases, rehabilitation might be the most technically and economically feasible alternative. O&M of facilities should be made adequate in irrigation projects.

The region needs to find appropriate means to achieve greater efficiency and equity in irrigation systems, as this would help not only to achieve greater levels of agricultural production with less water but also to solve some of the Mediterranean region's major environmental problems: water logging and salinity, declining groundwater tables, and shrinking lakes and seas. But finding such methods would require developing, testing, and implementing a wider range of alternative approaches, such as small-scale irrigation and conjunctive use and reuse of unconventional water resources (Chambers 1988). This would require much greater imagination and flexibility from irrigation policymakers, managers, and planners and require technological, managerial, and policy innovation and adaptation. In particular, it would require technologies, management practices, and policies that give greater control to end users to achieve the required increases in agriculture productivity.

Improvement of irrigation systems

In developing countries of the Mediterranean, the major physical and technical problems and constraints in irrigation systems are as follows:

- Inefficient water use;
- Shortage of water supply at the source;
- Poor canal regulation;
- Waterlogging and salinity;
- Poor O&M;
- Small-scale programs; and
- Scarce water resources.

Such problems and constraints require a set of common supporting actions:

- Development of adequate databases;

- Adaptive research;
- Institution-strengthening;
- Human-resource development;
- Improvements in socioeconomic analysis;
- Environmental protection;
- Technology transfer; and
- Infrastructure development.

In many cases, problems with technologies have been accumulating for a long time and their adverse impacts on system performance have increased because of nonexisting or ineffective solutions and neglect of maintenance.

O&M is one of the most underestimated aspects of irrigation projects in developing countries. As a result, the efficiency of projects continues to decline; in crisis situations, problems become too complex for technical resolution, and it turns out regular maintenance would have cost less than solving these problems.

Use of efficient irrigation technologies

In the majority of southern Mediterranean countries, any action aimed at economy in the use of water will have an important impact on preventing the destruction of basic development structures.

More effort should be made to introduce modern irrigation techniques into the region, which still makes very limited use of these techniques. Egypt uses modern farm irrigation methods (sprinkler and drip) on more than 27% of its irrigated land; Morocco, some 16%; and Tunisia and Syria, only 11 and 1%.

The major constraints to the expansion of such technologies are mainly the high operating costs, particularly the energy costs. Another major constraint is the lack of appropriate maintenance services for modern irrigation equipment. So far, few countries have reached a reasonable level of self-sufficiency in production of modern irrigation equipment. Locally made irrigation components are sometimes of poor quality, owing to a lack of expertise, low-quality materials, and lack of coordination between research institutions and industries. Irrigation equipment manufacturing in some Arab countries is too weak to provide adequate supplies for the development of modern irrigation systems.

Countries in the region need to carefully select and adapt modern irrigation techniques to local physical, agronomic, and socioeconomic conditions and the technical and managerial skills of local farmers. Upgrading existing irrigation schemes should, in most cases, follow pilot schemes to test alternative design concepts. Costly improved technologies are only justifiable if farmers can fully exploit the agronomic and economic potential of these technologies.

Water optimization: crop water requirements and irrigation scheduling

Research to optimize water application to various crops on diverse soil types, irrigation systems, and climatic conditions should continue to provide better knowledge on soil–water–plant relationships, and the concept of an optimal water supply. A priority in research should be to develop the management of irrigated crops to cope with droughts. In addition, researchers should consider the link between crop water requirements and the reliability of irrigation schemes.

Reallocation of irrigation water supply to crops with higher value and lower water consumption

Crop rotation is essential to irrigation water-demand management. Farmers should use crops with higher value and lower water consumption.

In most Mediterranean countries, national policies to achieve food self-sufficiency influence allocations of irrigation water heavily. As a result, the current cropping patterns contribute to the consumption of large amounts of water at a time when countries seek greater water savings and are economizing on the use of irrigation water to avoid the foreseeable conflicts between users.

For instance, cereals — especially rice and sugar cane — dominate agricultural production in Egypt and receive 25–30% of its irrigation water. Free water supplied in Egypt makes these crops profitable to farmers. Wheat is also a major crop in the region, accounting for 35% of Morocco's total agricultural production. Where cropping patterns lead to greater use of irrigation water, consideration should be given measuring the cost of water allocated to crop production.

The Mediterranean region needs new strategies to change cropping patterns to suit future water allocation. Such strategies should take the availability of water supply into consideration and use economic reforms and structural adjustments, including private-sector development, privatization, and trade and price liberalization. Countries in the region should also focus on lifting controls on agricultural crop patterns and shifting production to more profitable crops.

Irrigated water-use perspectives

Over the next 25 years, the region will have to divert sustainable quantities of freshwater from agriculture to industry and households. Irrigated agriculture will face two challenges, those of water shortage and dwindling financial resources. Despite these challenges, irrigated agriculture will have to supply not only the water demands of the other sectors but also 70–75% of additional food-grain requirements of developing countries in the region. This will be impossible without water-demand management in all sectors and the agricultural sector in particular. The region will need to find appropriate ways to achieve greater efficiency, better savings in water losses, and an equitable distribution of irrigation water. This will require developing, testing, and implementing a wider range of alternative approaches and greater imagination and flexibility from irrigation policymakers, managers, and planners. They will need to improve procedures and practices for assessing irrigation performance at all levels with better systems to manage the conveyance, allocation, and distribution of water.

Means of adoption

As an integral part of water management, the adoption of water-demand management involves the following steps:

- Formulating and evaluating demand reduction approaches and strategies as complements to, or substitutes for, supply augmentation projects;

- Using water pricing as a tool for demand management, including volumetric pricing of supply or waste water, on the basis of marginal supply or disposal costs, along with increasing block rates;

- Using efficient technical means to reduce urban water use and conveyances losses in the supply system, including changes in plumbing codes to require water-saving plumbing fixtures, programs of leak detection and control, and sustained maintenance;

- Recycling and other technical means to reduce withdrawal rates of water for industry, especially for cooling purposes;

- Using technical means to reduce the use of irrigation water, including drip and sprinkler irrigation, land-leveling and canal-lining, along with institutional means such as modifying water-rights systems to encourage efficient use; and

- Use of lower grade water for certain domestic, commercial, industrial, and agricultural purposes, which often involves installing dual-water supply systems.

Water-demand perspectives

Figure 7 shows water demand in the region for 1990, 2010, and 2025. Water demand will clearly increase progressively over the next 25 years. Globally, for the whole Mediterranean region, water demand will increase nearly 50% in 2025 over actual demand in 1990.

The question emerging nowadays is how to meet this ample water demand at a time when pressures on resources are increasing and it is becoming increasingly expensive to mobilize these resources. Before answering this question, one should first wonder about the efficiency of current water use.

Sectorial water losses

Overall, the majority of Mediterranean countries appear to make poor or little use of much of their water. Even where water is scarce, the efficiency of the use of drinking and irrigation water is far from satisfactory.

The following is an outline of the major water losses and inefficiencies in the various sectors (also see Figure 8):

- *Drinking water sector* — At least one-third of the drinking water for towns and villages leaks out through the network or wasteful misuse, thus wasting billions of dollars each year.

- *Industry sector* — Many industries use and lower the quality of water far in excess of their needs. Here again, one sees defects in recycling, leakage, loss, and inefficient production processes.

- *Irrigation sector* — Almost half of the water supplied for irrigation never actually gets to the field. This is due to leakage, badly adjusted modes of supply, low efficiency, and excessive consumer orientation of crops.

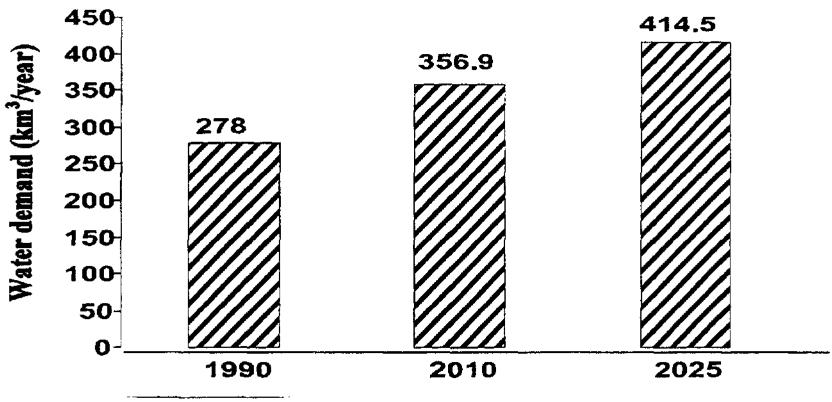


Figure 7. Actual (1990) and foreseen water demand (2010 and 2025). Source: Hamdy and Lacirignola (1999).

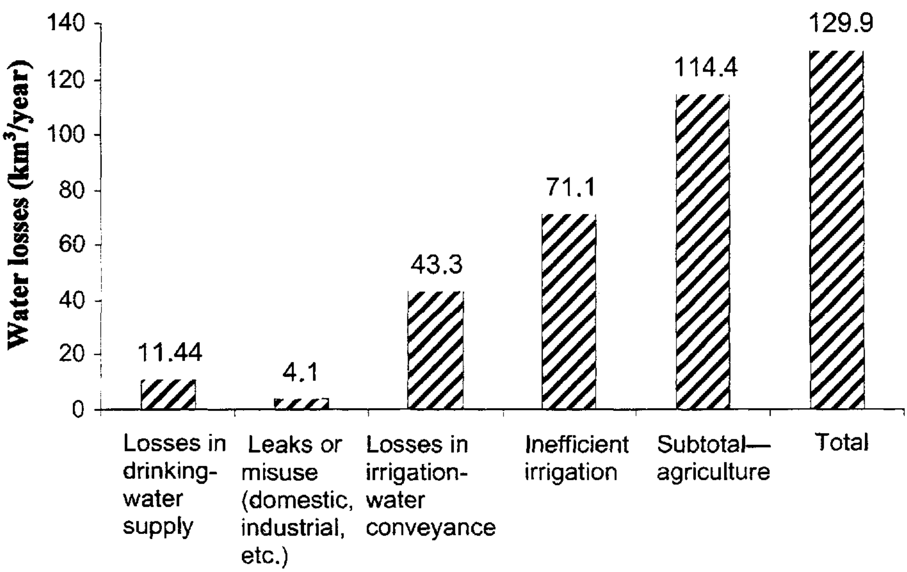


Figure 8. Actual losses of water per sector. Source: Hamdy and Lacirignola (1999).

Relevant to the specific situation of the Mediterranean is the general statement of the Food and Agriculture Organization of the United Nations in its annual report on world nutrition and agriculture (FAO 1993), that waste accounts for up to 60% of water drawn and pumped for irrigation.

Actual water losses, that is, inefficiencies per sector for the Mediterranean (Figure 8), occur mainly in the irrigation sector, where actual water losses approach 115 km^3/year, or nearly 88% of the total water losses.

Water-demand management and sectorial water savings

The way to water savings and reuse, whenever possible, is still open. Mediterranean countries could save and use a high proportion of the major water losses in the various water sectors through the use of technologies and methods available today.

However, water conservation efforts almost show decreasing profitability and increasing cost. Planners need to estimate exactly how much unused water the region could save and how much this would cost. They need to quantify the gains expected from reducing losses in the production and distribution system, as well as consumers' waste, and from modifying the exploitation system, especially in the agricultural sector.

The majority of the Mediterranean countries have great opportunities to save and reuse significant volumes of water through better use of the technical and economic tools and the institutional and human-resource capacities they already have. Countries in the region could reduce losses and leaks to save at least 50% of drinking water; and through recycling, industry could reduce its water consumption by nearly 50%. Although both the drinking and industrial sectors could thus save water, the greatest savings would be in the irrigation sector (Figure 9).

Southern Mediterranean countries, which allocate more than 80% of their water resources to agriculture, should strive to increase the efficiency of irrigation, as the opportunity to save water is notably higher there than in other sectors.

For instance, reducing transport losses by 50% and improving irrigation efficiency from 40–50% to 80% could provide savings of nearly 52 km^3/year, or more than 40% of total actual water losses in the region, and thus provide an additional supply of nearly 20% of the actual demand. Possible savings in irrigation constitute more than 70% of total water savings.

Although the drinking-water sector's contribution to total water savings would be the lowest among all the sectors (Figure 9) it would be of greatest value, owing to the higher cost of producing and distributing drinking water.

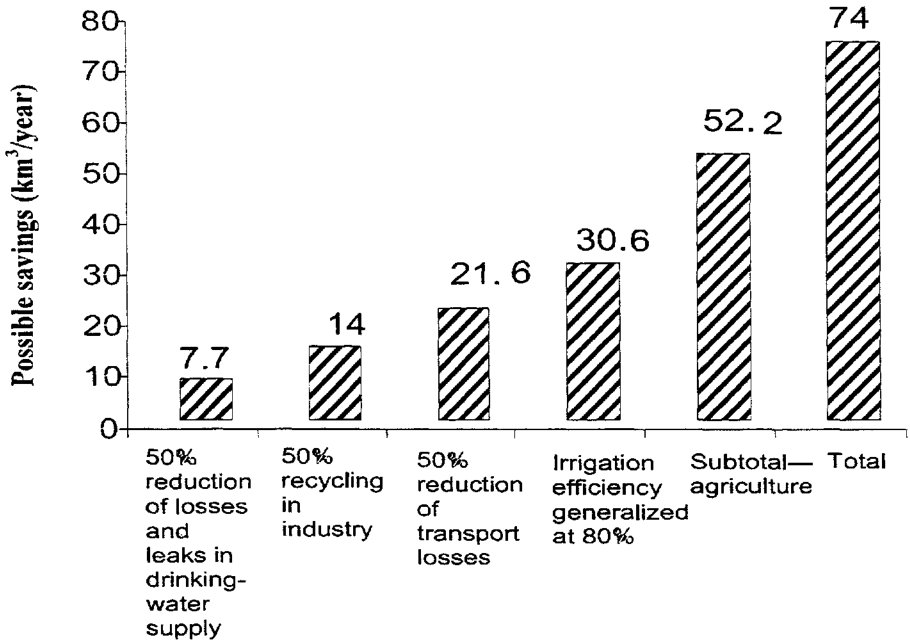


Figure 9. Possible water savings by sector with reference to the current water demand. *Source:* Hamdy and Lacirignola (1999).

These figures are only indicative, but they help to quantify the potential gains in each water sector. Water sectorial use should be the subject of feasibility studies in each country in the region, according to its socioeconomic and political situation.

Particularly in the arid and semi-arid regions, the whole water-resources situation in the Mediterranean — nowadays dramatic and complex — could change completely, showing a new, more promising picture, with more available water, less water loss and misuse, and smaller foreseen demand (Figure 10). However, to bring its water demand into line with its natural renewable water resources, the Mediterranean region must integrate the technical, social, and economic aspects of its water resources into an overall demand management strategy.

We must go beyond the symptoms to the causes of the problems and take new approaches to meet changing realities. We need new mechanisms to protect the resource and allocate diminishing water supplies to increasing and competing uses. Anticipatory and preventive approaches are therefore needed that fully consider the social, economic, and environmental aspects of the water resource.

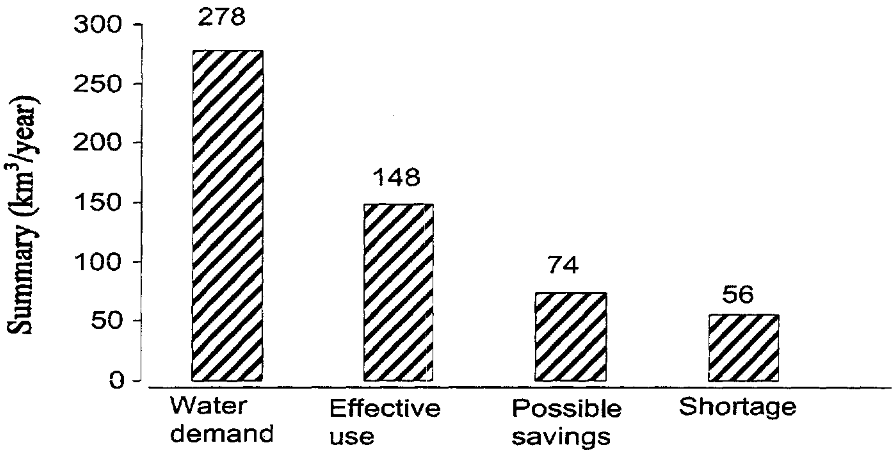


Figure 10. Summary of the situation (assuming the possible savings), 1990. Source: Hamdy and Lacirignola (1999).

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Chapter 2

Trickle Irrigation Experiments in Turkey

Osman Tekinel and Riza Kanber

Introduction

In recent years, farmers have made wide use of pressurized irrigation systems to increase crop yield. The drip (trickle) irrigation system is the most important of these systems and has contributed to a marked increase of yield under open-field and greenhouse conditions in past decades in Turkey. Its use is increasing rapidly for vegetable and field crops (Oron 1984; Tekinel et al. 1989). Greenhouse crops are also rapidly expanding in the Mediterranean region of Turkey.

Farm irrigation systems must supply water at rates, in quantities, and at times required to meet crop irrigation requirements and schedules. They divert water from a source, convey it to a cropped area, and distribute it over this area. In addition, the farm irrigation system must facilitate management by providing a means to measure and control flow.

Trickle irrigation relies on the concepts of irrigating only the root zone of a crop and maintaining the water content of the root zone at near optimum level. Irrigating only a portion of the land surface limits evaporation, reduces weed growth, and minimizes interruption of cultural operations. Maintaining a near-optimum water content in the root zone usually involves frequent application of small amounts of water (James 1988). These small amounts of water prove the high water-use efficiency (WUE) and higher yield and quality of crop obtained through drip irrigation.

WUE is calculated as units of dry matter produced per unit of irrigation water (Teare 1973). WUE as a function of radiation ensures energy for growth and transpiration of green plants. Plants grown under optimum conditions use water efficiently, but high-yielding crops range widely in WUE and these differences may stem from the use of diverse irrigation methods.

Comparison of irrigation methods is complicated by subtle, but often significant, differences in cultural practices (Wamble and Farrar 1983). Applying fertilizer with the water in one method and not in another can cause significant differences in growth, development, and yield. However, diverse water application and distribution efficiencies related to each irrigation method may also cause differences in nutrients, salt, and water distribution in soil profile.

The trickle irrigation method

The trickle system transports water through an extensive pipeline network to the soil near the plant and puts the water directly into the root zone. Trickle irrigation methods are high frequency–low volume, localized over a long period of application, have a low-pressure requirement, and apply water near or into the plant's root zone (Bucks and Davis 1986).

Israel started using the modern-day surface trickle system in 1963, and the United States started using it in 1964. Today, studies are done on the design, operation, and management principles of the trickle system (Davely et al. 1973; Jobling 1973; Keller and Karmeli 1975; Goldberg et al. 1976; Merriam and Keller 1978; Howel et al. 1981; Nakayama and Bucks 1986; Keller and Bliesner 1990; Kanber 1999). Its advantages, disadvantages, and the effects on the crop yield are subjects of intensive study throughout the world (Schweers and Grimes 1976; Maber 1979; Mostaghimi et al. 1981; Pai Wu 1982; Armstrong and Wilson 1982; Oron et al. 1982; Wamble and Farrar 1983; Oron 1984; Tekinel et al. 1989; Tekinel and Çevik 1993; Yavuz 1993; Çetin 1997; Ertek 1998; Keser 1998; Şenyiğit 1998; Kanber 1999).

Drip irrigation has contributed to a marked increase in agricultural yield over the past decade. The system transports water directly to the plant and its roots for ready use. One snag in this technique is that, in contrast to the other methods, it is not applicable to all plants and land types. Before and following the years of World War II, British farmers used plastic pipes in drip irrigation on land and in greenhouses (Goldberg et al. 1976; Hall 1985). Publications on the present-day surface trickle system began to appear from Israel in 1963 and United States in 1964, although research and development in both countries started some years before (Bucks and Davis 1986). Several researchers in the 1970s and 1980s studied design and project planning for drip irrigation systems (Jobling 1973; Keller and Karmeli 1975; Goldberg et al. 1976; Merriam and Keller 1978; Dasberg and Bresler 1985; Nakayama and Bucks 1986; Cuenca 1989; Keller and Bliesner 1990). James (1988) studied the advantages and disadvantages of the system.

Because it is a low-pressure system, drip irrigation is also called low-pressure irrigation. It takes water through drippers or injectors. Water leaves the dripper at zero pressure and gravity moves it to the soil and downward. The distribution in the soil has the shape of a dry onion head. The lateral flow of the water in the soil limits the area each dripper wets.

A drip irrigation system comprises a pump, control unit, network, and drippers. A schematic diagram for a typical trickle system is given in Figure 1. The

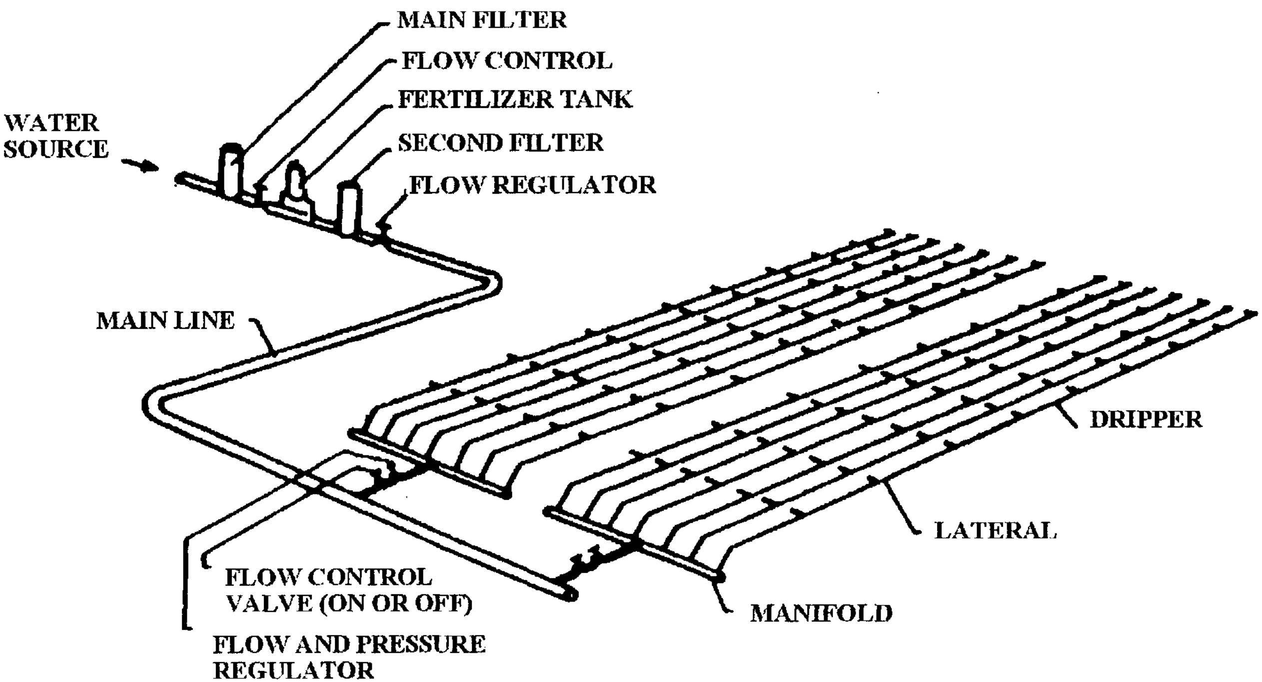

Figure 1. A basic trickle irrigation layout. Source: James (1988).

network comprises the mains, manifolds, and drippers. Although this system may use all the water resources, farmers should take care to ensure the water contains no sediments or floating matter.

The dripper outputs vary 1–10 L/hour, depending on their use, operating pressure, and type. Fruit orchards require flow rates ranging 4–10 L/hour, but the vegetables can do with 1–2 L/hour.

The following is a summary of the advantages of drip irrigation systems:

- Give more and better output, because these systems maintain the soil moisture at a high enough level to avoid putting plants under water stress;
- Use problematic soils and waters;
- Require no land levelling;
- Irrigate more land with less water;
- Irrigate with very high efficiency;
- Operate easily;
- Give water with fertilizers and pesticides; and
- Keep disease and pest development low.

Their limitations are as follows:

- The initial investment costs are rather high;
- Declogging is difficult and time consuming;
- Salinity is higher on the soil surface and between two drippers;
- These systems wet only a part of the plant root where shrinkages and output losses may occur with insufficient water or nutrients;
- Strong winds may fell large trees;

- These systems require a well-trained workforce; and

- Dust problems may arise in dry strips.

When all the advantages and drawbacks of drip irrigation systems are taken into account, they are preferable to other systems. In fact, the abundant high-quality crop production farmers obtain using these systems can compensate for their high investment costs. Likewise, in areas with scarce or expensive or with constraints on traditional irrigation systems, drip irrigation may be a sound choice.

Drip irrigation systems totally abandon the classical evapotranspiration concept, because the evaporation from the soil surface is almost zero. They maintain the moisture level in the soil at slightly over field capacity. As a result of this irrigation continuing throughout the year, the plant transpiration is at its highest potential, and the potential evapotranspiration is equal to the potential transpiration.

The techniques of crop water requirement

Crop water requirements

The climatic variables referred to in the preceding paragraphs influence the amount of water used by the plants. To live and grow, plants need soil, sunlight, air, and water. Water is an essential component of all plant tissues and fulfils three primary functions:

- Keeping plants erect by filling the cells in the plant tissue;

- Acting as a cooling agent in evaporating from the leaves, preventing overheating under hot conditions; and

- Carrying nutrients in solution from the soil into the plants through their roots.

The plant biomass is a product of sunlight, carbon dioxide, water, and nutrients from the soil (James 1988; Cuenca 1989).

The amount of water plants consume is equal to their evapotranspiration, which determines what quantity of irrigation water the farmer should apply (Jensen et al. 1990). The plant's evapotranspiration varies with climatic conditions in the same way as open water evaporation. Where the climate is hot and dry, the rate of evapotranspiration is high; where it is cool or humid, the rate is low. Where the wind blows, it is higher than where the air is still. Like rainfall and evaporation, evapotranspiration is expressed in millimetres of water depth; and the rate of evapotranspiration, in millimetres per hour.

"Consumptive use," a term that originated in the United States, describes the quantities of water used by land to support vegetation and crops. This is the same quantity as evapotranspiration and is also expressed in millimetres of water depth. Evapotranspiration is not easy to measure accurately, but researchers can estimate using climatic data (Doorenbos and Pruitt 1977; Jensen et al. 1990).

Estimation techniques

Under the same climatic conditions, diverse crops require diverse amounts of water, and a particular crop's quantity of water varies with its stage of growth. Initially, during seeding, sprouting, and early growth, a crop uses water at a fairly slow rate. As the crop develops, this rate increases, reaching a maximum in most instances at the approach of flowering and then declining toward plant maturity (Doorenbos and Pruitt 1977).

The actual amount of water used by a crop is determined by the following equation:

$$ET_c = K_c \times ET_0 \qquad [1]$$

where ET_c is crop evapotranspiration; ET_0 is grass-reference evapotranspiration; and K_c is crop coefficient. The crop coefficient may vary 0.3–0.35 during initial growth to more than 1.0 at mid-growth, and then fall below 1.0. The maximum crop water requirements for irrigation systems design are the significant quantities the crop needs. Figure 2 shows a typical crop-coefficient curve. Stages of growth are shown as a percentage of the total growing period, and this curve indicates how the crop coefficient changes with growth for most crops. However, crops differ, and Table 1 gives crop coefficients for some selected crops at mid-season and at final stage of growth under both humid and arid conditions and the ranges of growing periods.

Crop water consumption may be measured either experimentally, using the water-balance approach, or through micrometeorological methods. If neither is available, empirical equations are the solution.

The experimental approach is expensive, difficult, and time consuming. For this reason, the empirical equations are often used to estimate water consumption. Semi-arid countries, like those around the Mediterranean, may use several equations. Penman–Monteith, US Department of Agriculture–Blaney Criddle, Hargreaves, panevaporation, radiation, and the like are only a few. Several studies in

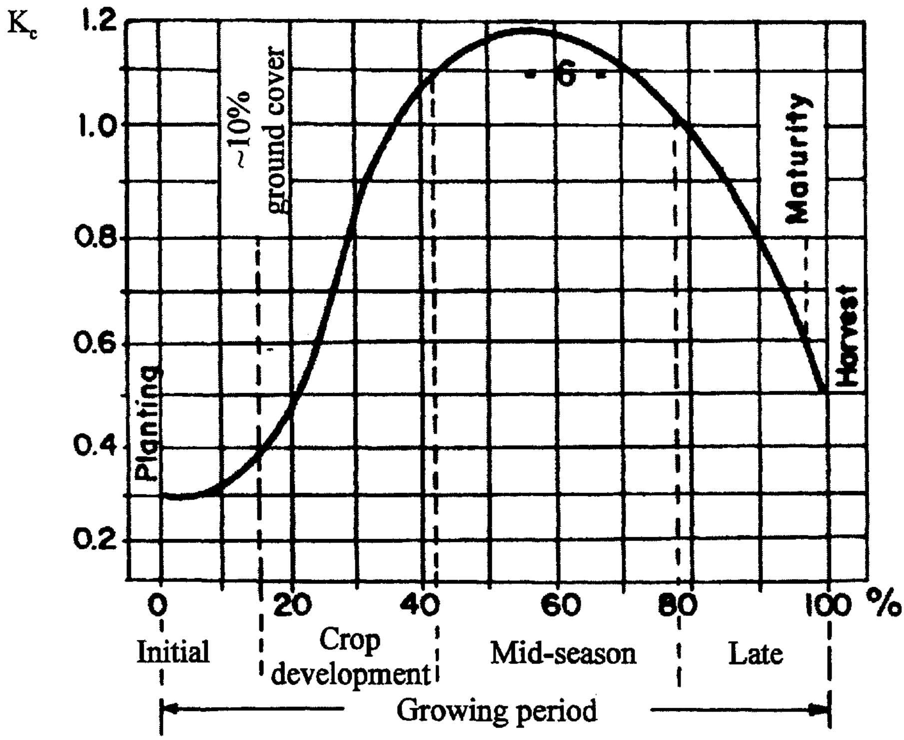

Figure 2. Typical crop-coefficient curve. Note: K_c is the crop coefficient. Source: Tekinel and Çevik (1993).

Table 1. Crop coefficients for various crops and their growing periods.

Crop	Relative humidity (more than humid) Mid-seasons	Relative humidity (more than humid) Final growth	Relative humidity (less than arid) Mid-seasons	Relative humidity (less than arid) 20% final growth	Growing period (days)
Barley, wheat	1.10	0.25	1.20	0.20	12–165
Green beans	0.95	0.85	1.00	0.90	75–90
Maize	1.10	0.55	1.20	0.60	80–110
Sorghum	1.05	0.30	1.15	0.25	105–140
Cotton	1.10	0.50	1.15	0.55	120–130
Tomatoes	1.10	0.65	1.20	0.65	180–195
Cabbage		0.60	1.20	0.65	135–180
Cauliflower	1.00	0.85	1.10	0.95	80–95

Source: Doorenbos and Pruitt (1977)

Turkey revealed that the first four approaches yield rather reliable results (Kanber 1977; Kanber and Kırda 1984; Tekinel and Kanber 1988).

Deciding when to irrigate

Techniques for determining irrigation time

Extension workers and farmers can use several methods to determine when to irrigate. James (1988) classified these methods as plant indicators, soil indicators, and water-budget techniques. Plant and soil indicators involve monitoring the plant and soil, respectively, and the water-budgeted technique relies on calculation or measurement of the elements in the water-budgeted equation.

As the primary objective of irrigation is to supply plants with water when they need it, monitoring plants is the most direct method of determining when to irrigate. Normally, a farmer or extension worker needs to relate plant parameters to soil water content to determine the amount of irrigation. Many books and articles give the required instrument or procedures, or both, and the principles, advantages, and disadvantages of several plant indicators. Some important plant indicators are appearance and growth, leaf temperature, leaf water potential, and stomatal resistance.

Using soil indicators for irrigation-scheduling involves determining the current water content of soil, comparing it to a predetermined minimum, and irrigating to maintain it in the soil. Farmers often vary the minimum water content, depending on the growth stage, especially in deficit irrigation schedules. Soil indicators of the best time to irrigate also provide data to estimate the amount of water to apply per irrigation. The many soil indicators include appearance and feel, gravimetric sampling, porous blocks, neutron scattering, and tensiometers.

Tensiometers used to determine when to irrigate

Tensiometers, used to determine the correct time to irrigate, have also come into wide use, for vegetables grown in glass houses and for open field crops (Tekinel and Çevik 1993).

In the past 20–25 years, tensiometers have been in wide use in determining when to irrigate, especially in greenhouses of the western Mediterranean coast of Anatolia. Many tensiometers are commercially available to measure soil water potential. Tensiometers provide measurements of soil water potential related to soil water content, using the characteristic curve of the soil. They may interfere with cultivation and require considerable time to install and maintain, and they have a fairly limited range of operation (0–80 cb).

The tensiometer completely eliminates the need for laborious soil sampling, laboratory tests, etc. A tensiometer station located in a "key area" of the field or the greenhouse supplies continuous monitoring of the moisture available to the crop. In general, the tensiometer prevents overirrigation and waste of water and soil nutrients (Figure 3).

A tensiometer is a sealed water-filled tube, equipped with a porous tip installed in the ground to the desired root zone (Figure 4). In dry soil, water is drawn out of the instrument, reducing the water volume in it and creating a partial vacuum. This is registered on the gauge. The drier the soil, the higher the reading. Irrigation reverses this action. The vacuum created by dry soil draws water back into the instrument from the soil. This in turn results in a lower gauge reading.

The instrument is in effect a "dummy root," equipped with a gauge that continuously registers how hard the roots are working. A gauge reading of 50 indicates the same amount of moisture whether in sandy or clay soil. Because of the tensiometer's unique principle of operation, it needs no calibrations, under normal operating conditions, for various types of soil. The extension worker or grower can plot the tensiometer readings on a graph during the growing season. Such a record is useful in planning future irrigation requirements and making year-to-year comparisons. Generally, tensiometers continuously show the available soil moisture in the crop's root zone.

The tensiometer covers the entire range of soil moisture required for maximum growth. Growers quickly learn the range of tensiometer readings in which they should start or stop irrigation to produce best results for their crops and conditions. The following interpretations of tensiometer readings have proven practical or useful under field conditions (also see Figure 5):

- *Readings 0–10: Saturated soil* — These readings often occur for a day or two following irrigations. Continued readings in this range indicate overirrigation, danger of waterlogged soils, inadequate root aeration, root rot, or high watertable.

- *Readings 10–30: Field capacity* — Growers should discontinue irrigations when readings in this range occur, to prevent waste of water through percolation and waste of nutrients through leaching.

- *Readings 30–60: Usual range for starting irrigations* — Root aeration occurs anywhere in this range. In general, in hot dry climates or coarse-textured soils, farmers should start irrigating when they see readings in

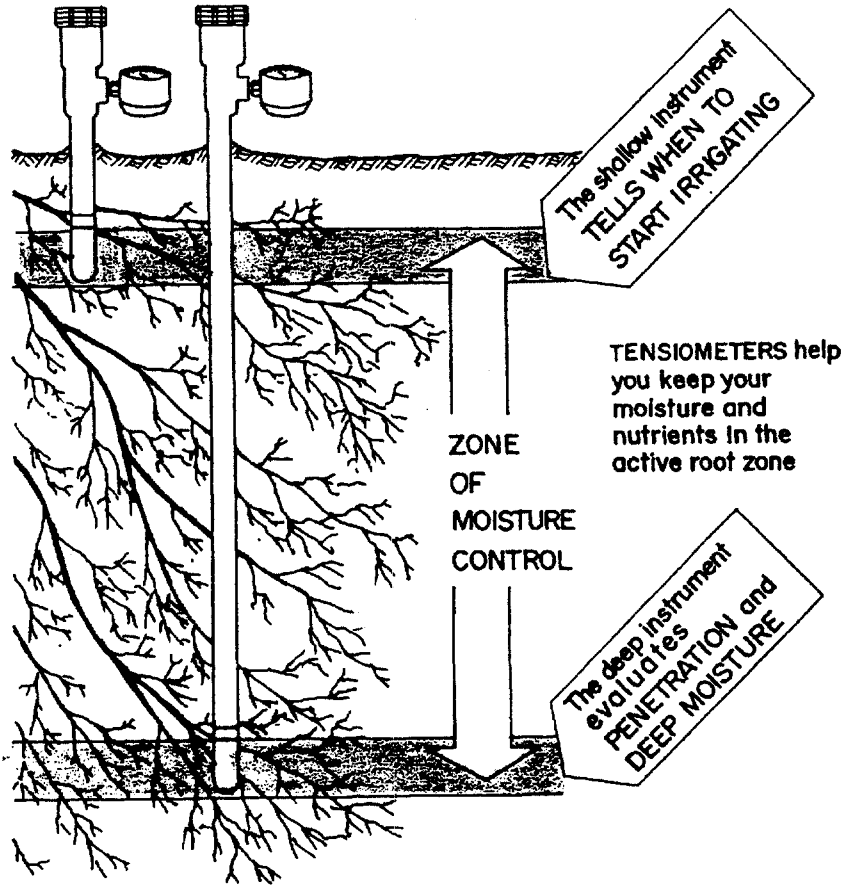

Figure 3. Tensiometers prevent overirrigation and waste of water and soil nutrients. Source: Tekinel and Çevik (1993).

the lower part of this range; in the upper part of this range, in cool, humid climates or soils with high water-holding capacity. Starting irrigations in this range ensures readily available soil moisture at all times, which is essential for maximum growth. It also provides a safety factor, with a reserve of soil moisture to compensate for such practical problems as delayed irrigations or inability to obtain a uniform distribution of water to all portions of the crop.

- *Readings 70 and higher: Stress range* — A reading of 70 does not necessarily indicate that the crop is using all available moisture, but that readily available moisture is getting dangerously low for ensuring maximum growth.

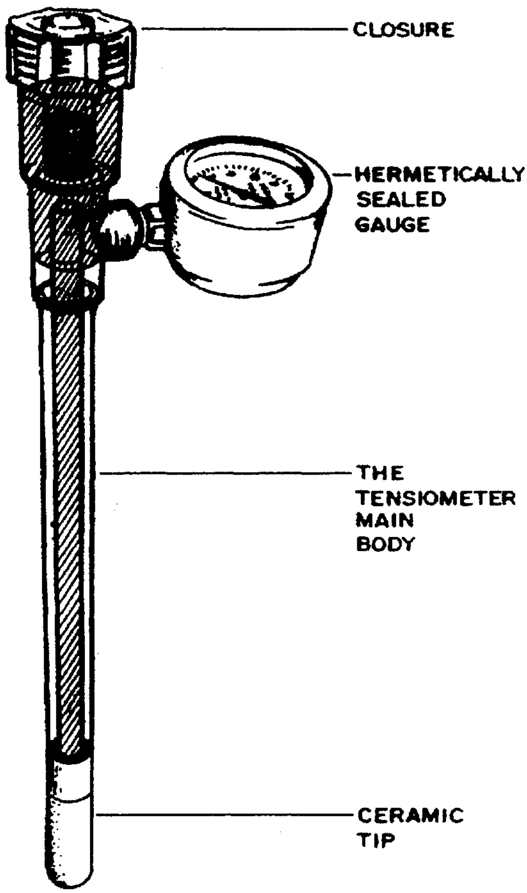

Figure 4. Typical tensiometer and its parts. Source: James (1988).

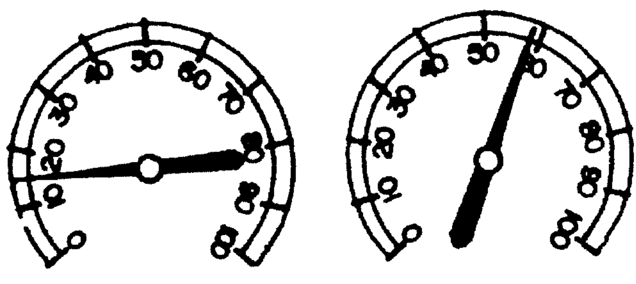

Figure 5. Tensiometer readings. Source: James (1988). Note: The reading on the left says soil has adequate water; the one on the right says soil moisture is low.

- *Readings of 80–85: Top range of accuracy of the tensiometers* — The number of tensiometers for an installation varies widely with crop and local conditions. Under the most favourable conditions, one station may be adequate for 1 decare of greenhouse (1 decare = 4.05 ha) (Figure 6).

Growers set tensiometers in "stations," which establish "zones of moisture control" to a depth depending on the depth of the active root system. The depth of the root system determines the depth or depths of the instruments at each station. With furrow irrigation, the grower must consider the depth of the furrow to determine that of the tensiometer (Figure 7). For shallow-rooted crops, one instrument per station is adequate. When the plant is young, the grower sets the tensiometer at only a few centimetres deep. As the root system grows more extensive, the grower sets the tensiometer at greater depths, until the plants reach maximum root growth (Figure 8). You should never set a tensiometer in a hole. An incorrect application of a tensiometer is shown in Figure 9.

Tables 2 and 3 give recommended depths of tensiometer installation, and tensiometer placement depths help to determine the required lengths of tensiometers. When root systems are more than 30 cm, growers should use two instruments. Most crops have active root systems to 30–90 cm. For these crops, growers should install two depths per station. The grower should place the ceramic tip of the shallow instrument at about one-quarter of the actual depth of the root zone; and the deep instrument, at about three-quarters. When the tensiometer has indicated the soil moisture at these depths, the grower can accurately estimate moisture conditions throughout the root zone.

The plant obtains about 90% of its moisture requirements from the upper three-quarters of the root zone. The tensiometer stations, therefore, permit you to maintain the desired moisture condition in this area while preventing overirrigation and thereby conserve water and fertilizer. If you install a single instrument per station half way down the root zone for crops with root systems more than 45 cm deep, you'll fail to get the maximum benefit of tensiometers. Crops obtain about 70% of their moisture requirements from the upper half of the root zone. When growers install tensiometers too deeply, their plants may suffer stress before the gauge indicates it is time to irrigate. Without an instrument in the lower root zone, growers have no indication of when they have achieved penetration. Using settings at two depths instead of one doubles the grower's investment but controls soil moisture throughout a depth 6–10 times that of a single installation (Figures 10 and 11).

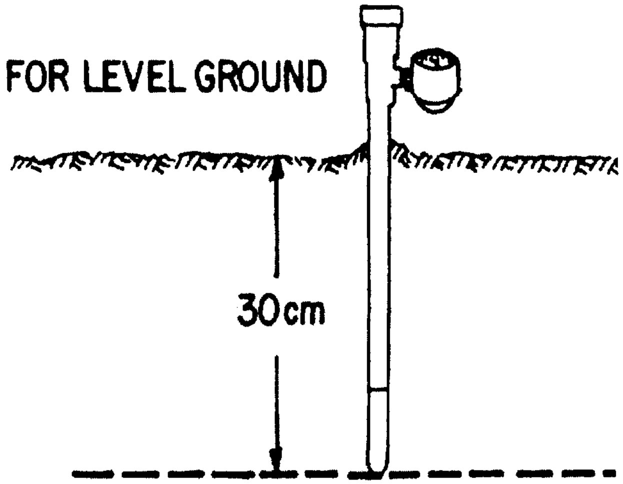

Figure 6. Tensiometer installation on level ground. Source: Tekinel and Çevik (1993).

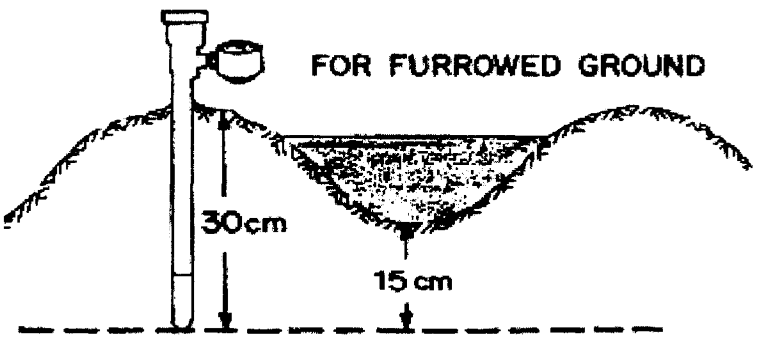

Figure 7. Tensiometer installation in furrow. Source: Tekinel and Çevik (1993).

Materials and methods

Experiments took place in three locations in the Mediterranean (Adana, Tarsus, and Alanya) and in one in the southeastern region of Turkey (Şanlıurfa) during 1980–1998. Some experiments took place under field conditions and others in greenhouses and in high tunnels. These studies examined various irrigation methods for citrus, banana, strawberry, tomato, pepper, eggplant, cotton, rose, and watermelon.

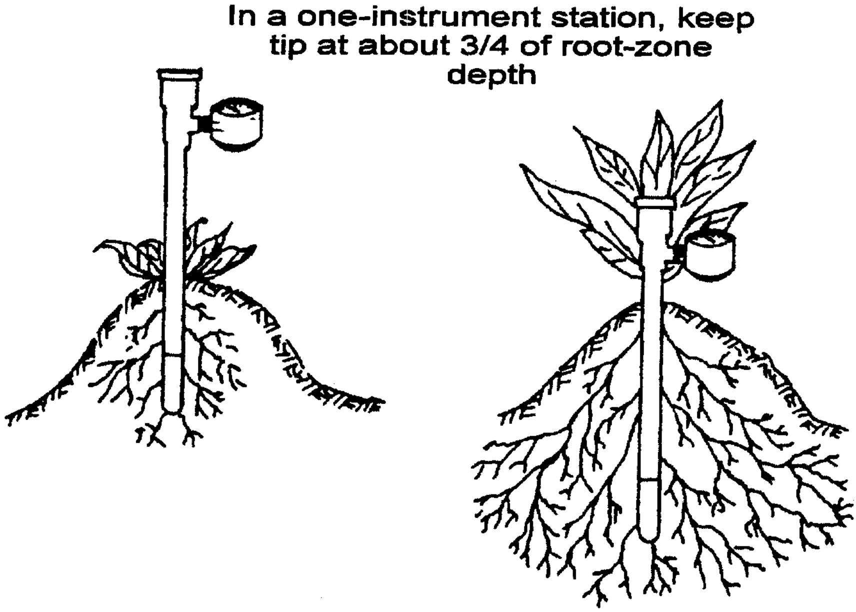

Figure 8. A one-instrument station. Source: Tekinel and Çevik (1993).

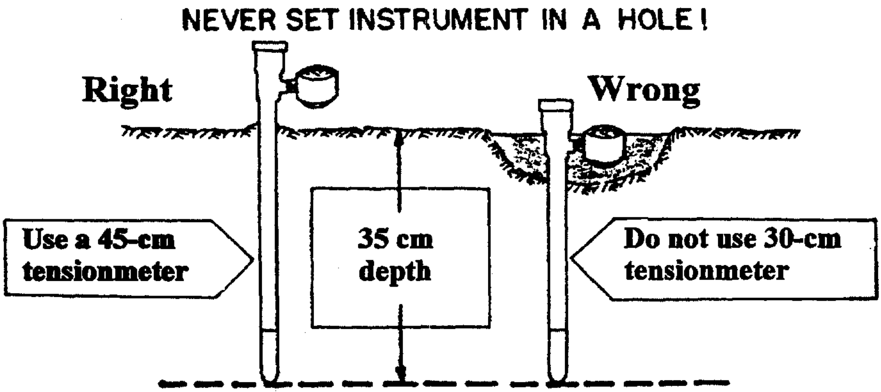

Figure 9. A wrong installation of a tensiometer. Source: Tekinel and Çevik (1993).

The greenhouses used in these studies had various areas, none smaller than 1 decare, and some open spaces and were covered by glass plates or plastic sheet. The high tunnels in some experiments were about 3 × 36 m and 2 m high, built using plastic to cover an iron shore, which was a monoblock with half-circle shape.

Table 2. Recommended depth for tensiometer.

Root system (cm)	Shallow instrument (cm)	Deep instrument (cm)
≤45	15–30	—
≤60	15–20	45
≤90	20–40	60
≤120	30–45	90

Source: Doorenbos and Kassam (1979).

Table 3. The placement of depths for tensiometers.

Crop	Shallow instrument (cm)	Deep instrument (cm)
Cabbage	30	50
Carnations	30	—
Carrots	30	60
Cauliflower	30	60
Celery	25	50
Cucumbers	30	45
Eggplant	30	45
Garlic	30	45
Lettuce	30	—
Melons	30	45
Onions	30	45
Peppers	35	50
Potatoes (Irish)	25	45
Potatoes (sweet)	45	60
Radishes	30	—
Spinach	30	45
Squash	35	50
Strawberries	15	30
Tomatoes	30	45
Watermelon	30	45

Source: Tekinel and Çevik (1993).

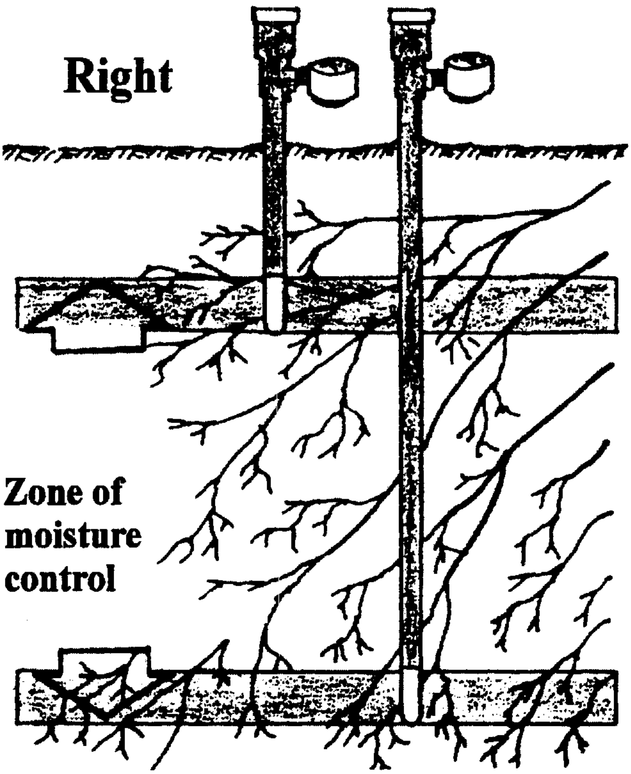

Figure 10. Zone of moisture control, with two instruments. Source: Tekinel and Çevik (1993).

The Mediterranean climate prevailed at the experimental sites. Average yearly temperature, humidity, free water-surface evaporation, and annual rainfall varied at 18–20°C, 60–70%, and 1500–1700 mm, 600–750 mm, respectively, except in Şanlıurfa. This region has a desert climate, with a dry hot summer and calm winter months. In Şanlıurfa region, the average yearly temperature, humidity, free water-surface evaporation are 17°C, 49%, and 2024 mm, respectively. However, this region received 399 mm rainfall, on average, over 40 years. Soils used were Mutlu series in Adana, Arikli series in Tarsus, and Harran series in Şanlıurfa (Table 4).

The experiments generally examined furrow, border (surface irrigation), sprinkler, and trickle irrigation methods. However, as some studies or experiments compared all of the irrigation methods, others only considered two of them.

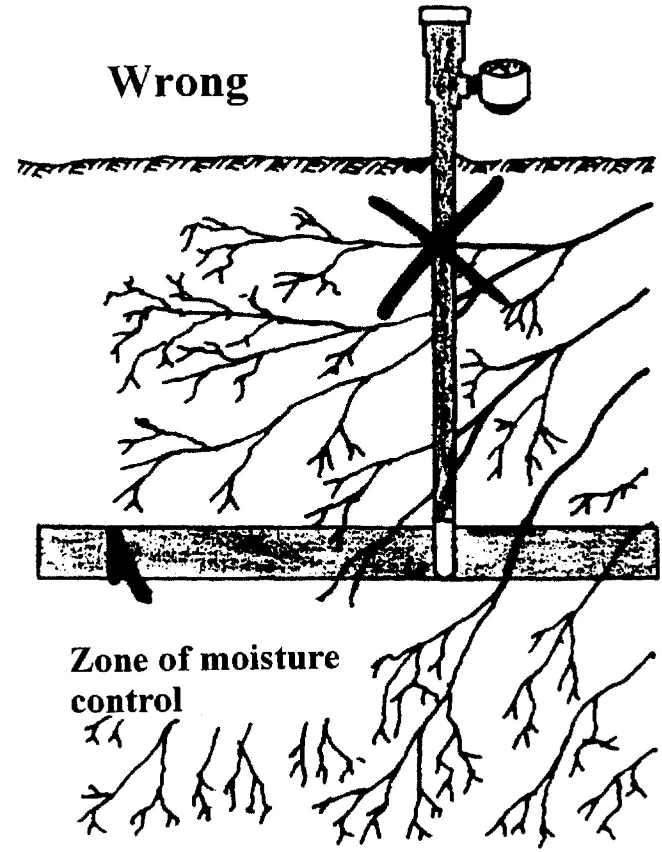

Figure 11. Zone of moisture control, with one instrument. Source: Tekinel and Çevik (1993).

Table 4. Sites and soil descriptions for experiments given their results.

Location	Soil series	Great soil	Available soil water (Pw)	Altitude (m)
Adana, 2 km south of the university	Mutlu soil series: fine clay loam	[a]	13	20
Tarsus, 45 km west of Adana	Arikli soil series: silty clay	[b]	13	12
Alanya, 90 km east of Antalya	Farm-orchard clay loam	[b]	16	7
Talat Demirören Station, 31 km south of Şanlıurfa	Harran soil series: red clay	[b]	20	410

[a] Palexerollic Chromo Xerent.
[b] Entic Chronoxerert.

The following equation determined the amount of irrigation water for the sprinkler and surface methods:

$$I = D_{fc} - D_{ml} \qquad [2]$$

where I is irrigation water; D_{fc} is soil water content at field capacity; and D_{ml} is soil water content at the time of irrigation. The soil water level in those methods varied 40–60% in a soil depth of 60–150 cm, depending on the crop. All treatment used the pounding-furrow method to apply irrigation water, with a flow meter and calibrated syphons.

Generally, equation [3] determined the irrigation water for the trickle method, based on a class-A evaporation pan:

$$V = K_{cp} \times E_p \times P_c \times A \qquad [3]$$

where, V is volume of irrigation water; K_{cp} is crop-pan coefficient; E_p is free water-surface evaporation; P_c is plant cover on the ground surface; and A is plot area. The experiments used various crop-pan coefficients and irrigation intervals (Table 5).

System operation was defined as the relationship between dripper-flow pressure and time and was calculated using equation [4],

$$T = \frac{V}{q \times n} \qquad [4]$$

where, T is irrigation duration; V is volume of net irrigation water; q is dripper flow; and n is number of dripper in a plot. Trickle lines were laid along one side of each row. Generally, drip irrigation used "in-line" and microtube-type emitters. Water from an irrigation canal passed through a sand filter and 400-mesh screen. A pump provided an average line pressure of 1.00–1.50 bar (1 bar = 100 kPa). A Venturi-type injector worked downstream from the filters, used to send liquid fertilizer through the system. Emitter spacing in strawberry and vegetables was about 50 cm; and the citrus and banana trees each had 6 emitters. Discharge rates of emitters were 3–4 L/hour. In Şanlıurfa, the microtube-type emitters had a 2.0-L/hour flow rate at 1.0-bar operating pressure, with 33-cm emitter spacing on the

Table 5. Irrigation intervals and crop-pan coefficients for chosen experiments.

Plant	Test site	Crop-pan coefficient	Irrigation interval	Experimental condition
Citrus	Adana	1.0	Daily and 2 days	Field
Citrus	Tarsus	0.60	2 days	Field
Banana	Alanya	At 25–30 cb in 30-cm depth		Field
Strawberry [a]	Adana	At 20 cb in 60-cm depth		Field
Strawberry	Tarsus	0.80	Daily	Field
Tomato	Adana	—	—	Greenhouse
Pepper	Adana	1.2	Daily and 3 days	High tunnel
Eggplant	Adana	1.2	Daily and 3 days	High tunnel
Cotton	Adana	1.0	10 days	Field
Cotton	Adana	0.91	7 days	Field
Cotton	Şanlıurfa	0.87	Varied	Field
Rose	Adana	1.0	Varied (2–6 days)	Greenhouse
Watermelon	Adana	1.0	Varied (9–12 days)	Field

[a] Irrigation is dropped at 0–10 cb.

line. The cotton experiments used in-line drippers with 60-cm spacing. They had a 2.0-L/hour flow rate at the 2.0-bar pressure. In some cotton experiments, the emitter spacing varied 30–60 cm, depending on irrigation programs. They were on-line types, with a 1.6-L/hour flow rate at 1.0-bar operating pressure. In the rose experiment, in-line drippers had 30-cm spacing. The operating pressure in the drip irrigation network was 0.75 bar, and flow rate of drippers was 2 L/hour. The in-line drippers had 50-cm spacing along the laterals in the watermelon experiment. In this study, the emitter discharge rate was 4.0 L/hour at 2-bar pressure. All experiments used polyethylene pipe with at least 16-mm diameter and 40-m length for lateral line. Soil moisture content in the root zone was measured using a neutron probe, tensiometers, gypsum blocks, and gravimetric method, depending on the type of irrigation. Cultural operations were the same for all irrigation methods, except that trickle plots were fertilized over several days, instead of a single banded application in furrow and sprinkler-irrigated plots.

Results of the trickle irrigation experiments

Open-field experiments

Under open-field conditions, many crops, such as strawberry, lemon, orange, and banana, were irrigated using various methods, including the drip technique. The results of these experiments are presented in Table 6.

The first crop, used for drip irrigation experiments, was strawberry in the Mediterranean region of Turkey. The first half of the 1970s was the time of adaptation of drip irrigation techniques in Turkey. Kanber and Derviş (1975) conducted the preliminary work on drip irrigation for strawberry. This experiment was very primitive and made the drip-system irrigation network using ordinary techniques. However, it involved taking no scientific results, only a demonstration for the farmers. Another experiment on strawberry took place in the Irrigation Engineering Department of Çukurova University, using two cultivars, Pochantos and Aliso. The yields of strawberry in the Adana experiments did not show any difference between irrigation methods (Tekinel et al. 1984), but the marketable yield from trickle was higher than that from other methods. An experiment in Tarsus was, again, on strawberry (Kanber et al. 1986). However, in this study, the effects of irrigation methods on yield were statistically different. Water use from trickle methods was 34% more than that in furrow. Yield from trickle irrigation was 12% more than in furrow. However, unmarketable yield decreased 17% with drip irrigation. WUE in trickle irrigation is higher, so it may be argued that higher yield was obtained from trickle method with less water (Table 6).

In orange experiments (Table 6), we used Magnum Bonum cultivar. Experimental trees in Adana were 25 years old. The results from Adana indicated that sprinkler irrigation increases the yield in compression with the drip and furrow methods (Çevik et al. 1982). Trickle irrigation's results were insignificant because of the root-development properties resulting from surface irrigation carried out for a long time. The values for WUE of sprinkler method were not higher than those for drip, and they varied 0–1.0. The Tarsus experiments used young trees, observing the growth of trees in trials during 1978–1988. The effects of irrigation methods on growth were found to be insignificant (Eylen et al. 1988). Only 1 or 2 years after planting, trickle method increased the growth. WUE values were low with both irrigation methods. However, they were higher than those from Adana. In contrast, trickle systems were profitable only for areas of more than 50 decares.

Özsan et al. (1983) also studied effects of irrigation methods on the lemon yield and growth in the same citrus irrigation program. Although tree growth was not affected by the irrigation techniques, the trickle irrigation positively increased

Table 6. Irrigation water use and yield with various irrigation methods.

Crop	Irrigation method	Irrigation water (mm)	Yield (t/ha)	WUE [a]
Strawberry (Adana)	Furrow		7.5	
	Drip	—	11.0	—
	Sprinkler		9.0	
Strawberry (Tarsus)	Furrow	400–650	12–13	0.3–0.2
	Drip	300–400	13–15	0.4
Orange (Adana)	Furrow	460–575	24.5–36.7	0.5–0.6
	Drip	151–299	20.1–37.3	1.3–1.2
	Sprinkler	344–430	31.0–42.4	0.9–1.0
Orange (Tarsus)	Drip	115–445	5.9–7.6	0.5–0.2
	Sprinkler (under tree)	670–844	13.6–13.3	0.2–0.16
Lemon	Furrow	1002–1336	2.2–2.8	0.02
	Drip	184–277	2.2–2.5	0.10–0.09
	Sprinkler (over tree)	1001	2.5–3.4	0.02–0.03
	Sprinkler (under tree)	1064–1463	2.5–2.8	0.02–0.01

Note: WUE, water-use efficiency.
[a] WUE = 100 × (yield / irrigation water).

the pomological properties. The highest yield resulted from use of the over-tree sprinkler, and the lowest resulted from planting in furrow. WUE was highest in drip irrigation.

Growers plant banana widely in the Mediterranean region, from Mersin to Antalya. Çevik et al. (1985) conducted the Antalya experiment in a farmer's garden. Irrigation water used in this study was of the quality of C_3S_2. According to the results, the trickle treatments received about 50% less than the trough-method plots. The yield per square centimetre of the stem cross section increased, and irrigation water was less in the drip method. The trickle method has advantages for irrigation of banana over the conventional method because of low-quality water and water-use economy.

After 1988, in the Mediterranean and southeastern regions of Turkey, work started on drip irrigation of some important crops, such as cotton. Çukurova is the place where cotton growing is the most wide spread in Turkey. Yavuz (1993) conducted a detailed experiment to determine suitable irrigation methods for cotton. Yavuz tested three irrigation methods, namely, furrow, drip, and sprinkler. In addition, this study included various management techniques for each irrigation method. For instance, furrow irrigation comprised ponded alternative furrows (PAF), free-end furrows (FEF), and ponded continuous-flow furrows (PCF). Drip irrigation used two emitter spacings (30 and 60 cm) and two planting techniques, traditional and double row in a single planting bed. Accordingly, the study used four drip irrigation treatments. In sprinkler irrigation, Yavuz evaluated various final irrigation dates and levels. Soil water observations in the free-end furrows determined the irrigation times for furrow and sprinkler methods. Yavuz calculated the amount of irrigation water to use in the plots on the basis of the amount needed to replenish the soil water deficit to field capacity. Drip irrigation used an irrigation interval of 7 days. Yavuz calculated the amount of the irrigation water for drip plots from cumulative free water evaporation, measured from class-A pan between the irrigation intervals.

The results are presented in Table 7. This table gives some measurements such as average irrigation water, evapotranspiration, and water losses from runoff and deep percolation. Table 7 shows no statistically significant difference between cotton yields from various irrigation methods. The highest yield, 326 kg/decare, appeared in the PCF treatment. However, the double-row drip irrigation treatment using 30-cm emitter spacing had also given a high yield after PCF. It should be noted that this treatment's water savings were almost 65% of those in the FEF treatment and 57% of those in PCF. Moreover, almost 50% of the irrigation water was runoff in the FEF treatment.

Irrigation efficiencies for treatments also differed. Table 8 shows some efficiency components such as application, requirement, infiltration, tail-water ratio, deep-percolation ratio, uniformity of Christiansen coefficient, distribution uniformity, and WUE, calculated for various irrigation methods. This table also gives infiltrated water estimated from net infiltration opportunity time.

The irrigation methods differed in their performances. The highest application efficiency was in sprinkler irrigation, at 92%. The ponded alternate furrow followed sprinkler irrigation, with 80%. The application efficiency of FEF was 67%, an acceptable value. All irrigation methods had acceptable efficiencies for cotton irrigation.

Çetin (1997) conducted another detailed experiment on irrigation of cotton in Şanlıurfa–Harran Plain to determine the effects of various irrigation methods

Table 7. Some average measurements for cotton irrigation methods.

Method [a]	Yield (kg/decare) [b]	Yield (%)	IR (mm)	IR (%)	ET (Mm)	Runoff (mm)	DP (mm)
PAF	298	91	465	40	610	—	99
FEF	312	96	1146	100	784	504	—
PCF	326	100	929	81	928	—	193
SI	255	78	929	81	961	—	95
DTd_2	207	64	175	15	542	—	—
DTd_1	250	77	349	30	705	—	—
DDd_2	289	89	203	18	557	—	—
DDd_1	316	97	404	35	756	—	—

Source: Yavuz (1993).

Note: DD, double-row drip irrigation; DP, deep percolation; DT, traditional drip irrigation; ET, evapotranspiration; FEF, free-end furrows; IR, irrigation water; PAF, ponded alternative furrows; PCF, ponded continuous flow furrows; SI, sprinkler irrigated.

[a] d_1, 30-cm emitter spacing; d_2, 60-cm emitter spacing.

[b] 1 decare = 0.1 ha.

(furrow, stationary sprinkler, stationary drip, mobile sprinkler, mobile drip, and low-energy precision application [LEPA]) and irrigation water levels on yield, quality, and WUE for cotton between 1991–1994. Çetin estimated the applied water for the methods of drip and furrow using cumulative pan evaporation of 50 ± 5 mm and 100 ± 10 mm at varying time intervals and adjusted coefficients of 0.6–1.8 as increased 0.3 increment (for furrow and drip). For sprinkler irrigation, Çetin calculated the amount of water given to the plots close to lateral line, using 100 ± 10 mm cumulative pan evaporation measured in a time interval and coefficient of 1.8.

The results showed that these irrigation methods have significant effects on the yield. Stationary drip gave the highest cotton yield, and the lowest yield from stationary sprinkler (Table 9). Amount of irrigation water stands to cotton yield in a quadratic relation (Figure 12). This figure shows that the yield increased to a peak and then decreased with irrigation water. However, WUEs in drip irrigation were high among the treatments at all water levels. The lowest values were from furrow methods at all water levels.

Maximum yield for cotton was 438, 363, and 328 kg/decare from drip, furrow, and sprinkler, respectively, with 898, 937, and 1106 mm of irrigation water. Çetin calculated the amounts of water, using pan evaporation coefficients of 0.87, 0.90, and 1.07. According to these results, the yield from drip irrigation method

Table 8. Performances of various cotton irrigation methods.

Method [a]	Zi	Ea	Er	Ei	TWR	DPR	UCC	DU	WUE
PAF	375	80	81	100	—	20	89	90	0.49
FEF	653	67	69	100	33	—	94	62	0.40
PCF	722	77	75	100	—	23	91	94	0.35
SI	834	92	85	100	—	8	100	100	0.27
									0.39
	Da	Eu	PELQ	AELQ	Dn				
DTd_2	8	90	91	78	7				0.39
DTd_1	16	82	74	71	12				0.36
DDd_2	9	70	63	61	6				0.54
DDd_1	15	76	68	66	11				0.43

Source: Yavuz (1993).

Note: AELQ, application efficiency; Da, average application depth; DD, double-row drip irrigation; Dn, minimum application depth; DT, traditional drip irrigation; DU, distribution uniformity; Ea, application; Ei, infiltration; Er, requirement; Eu, emission uniformity; FEF, free-end furrows; PAF, ponded alternative furrows; PCF, ponded continuous-flow furrows; PELQ, potential application efficiency; SI, sprinkler irrigated; TWR, tail-water ratio; UCC, uniformity of Christiansen coefficient; WUE, water-use efficiency.

[a] d_1, 30-cm emitter spacing; d_2, 60-cm emitter spacing.

was 34 and 24% more than those from furrow and sprinkler methods, respectively, and the yield from furrow was 11% more than that from sprinkler. Generally, the mobile irrigation systems (mobile drip and LEPA) gave lower cotton yields.

In Çukurova region, Ertek (1998) carried out an experiment to develop a suitable program for drip irrigation of cotton, as well as studying the possibility of using drip systems to irrigate cotton. The study took place in 1994 and 1995. Ertek used Çukurova-1518 variety cotton. The laterals were at 0.7-m intervals (a lateral for every crop row). Ertek determined the amount of irrigation water on the basis of free surface evaporation from a screened class-A pan. The treatment comprised two irrigation intervals (5 and 10 days), three plant-pan coefficients (0.75, 0.90, and 1.05), and two wetting percentages (0.70 and the cover percentage of crop). Ertek applied the first irrigation when the available soil moisture was at 40% in the 120-cm depth of the profile.

Average seasonal irrigation water varied 336–439 mm; seasonal evapotranspiration varied 468–580 mm; and the cotton yield varied 269–320 kg/decare (Table 10). Although the effect of irrigation interval and wetting percentage on

Table 9. Average irrigation water, yield, and WUEs for various cotton irrigation methods.

Furrow		Stationary sprinkler		Stationary drip		WUE (kg/ha per mm)		
IR (mm)	Yield (kg/decare)[a]	IR (mm)	Yield (kg/decare)	IR (mm)	Yield (kg/decare)	Furrow	Sprinkler	Drip
624	254	328	216	341	207	4.07	6.59	6.07
937	363	735	291	619	346	3.87	3.96	5.59
1248	385	1106	328	898	438	3.08	2.97	4.88
1561	397	1432	338	1144	489	2.54	2.36	4.27
1872	364	1664	350	1408	490	1.95	2.10	3.48
		1917	333				1.74	

Source: Çetin (1997).
Note: *IR*, *irrigation water*; WUE, water-use *efficiency*.
[a] 1 decare = 0.1 ha.

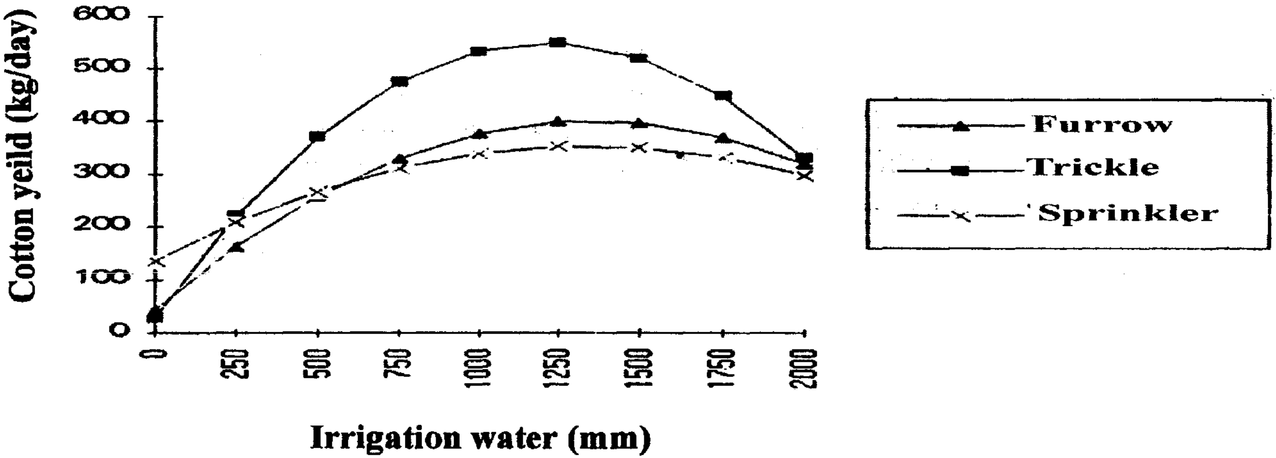

Figure 12. The relationships between cotton yield and amount of irrigation water for various irrigation methods. Source: Çetin (1997)

Table 10. Some results from drip irrigation of cotton on the Çukurova Plain.

Treatment [a,b]	IR (mm)	IR (%)	ET (mm)	Yield (kg/decare [c])	TWUE (kg/decare per mm)	IWUE (kg/decare per mm)	IR/ET (%)
$I_1Kcp_1P_1$	336	76	468	269	0.58	0.89	68
$I_1Kcp_2P_1$	360	82	490	279	0.58	0.86	69
$I_1Kcp_3P_1$	383	87	525	297	0.57	0.87	69
$I_1Kcp_1P_2$	370	84	496	283	0.59	0.85	71
$I_1Kcp_2P_2$	401	91	536	318	0.61	0.88	71
$I_1Kcp_3P_2$	431	98	564	299	0.53	0.75	73
$I_2Kcp_1P_1$	336	76	471	287	0.62	0.93	67
$I_2Kcp_2P_1$	360	82	491	292	0.61	0.90	69
$I_2Kcp_3P_1$	383	87	524	307	0.61	0.89	69
$I_2Kcp_1P_2$	376	86	516	311	0.62	0.92	68
$I_2Kcp_2P_2$	407	93	562	320	0.59	0.88	70
$I_2Kcp_3P_2$	439	100	580	317	0.56	0.79	72

Source: Ertek (1998).

Note: ET, evapotranspiration; I, interval; IR, irrigation water; IWUE, irrigation water-use efficiency; *K*cp, crop-pan coefficient; TWUE, total water-use efficiency.

[a] I_1, 5 days; I_2, 10 days.

[b] K_{cp1}, 0.75; K_{cp2}, 0.90; K_{cp3}, 1.05.

[c] 1 decare = 0.1 ha.

cotton yield was not significantly different for the first- and second-year plant-pan coefficient, the interaction of wetting percentage and crop-pan coefficient was significantly different at 5% between the treatments.

There were significant relationships between plant height, leaf-area index, development of plant covers, dry matter with both irrigation waters and evapotranspiration. Depending on the treatment, effective root-zone depth for cotton varied 88–111 cm. Total WUE and irrigation WUE varied 0.58–0.62 kg/decare per mm and 0.75–0.93 kg/decare per mm, respectively. The ratio of irrigation water to evapotranspiration was 68–73%. The salt accumulation at 15 cm from the dripper increased in the upper layer and gradually decreased toward the bottom. At 30 cm from the dripper, salt accumulation increased to near the wetted front.

Şenyiğit (1998) conducted an experiment on watermelon. This experiment studied various irrigation methods (sprinkler and drip), nitrogen forms (liquid and granule) and amounts (based on applied line source sprinkler), and two varieties of watermelon (Paladin and Madera). Şenyiğit carried out the study at the Research and Production Farm of the Agricultural Faculty of Çukurova University, during the 1996 and 1997 growing seasons.

Generally, Şenyiğit irrigated the plants at 5–12-day intervals. Free water-surface evaporation determined the amount of irrigation water. Şenyiğit estimated the irrigation water in the plot with drip irrigation based on an assumed irrigation of 70% per volume of the soil. Only the treatments with sprinkler and liquid nitrogen and with sprinkler and granule and liquid nitrogen had three nitrogen levels, providing a gradient during the irrigation season.

The greatest use of irrigation water was in the middle of June, when the fastest growth occurred. the amount of irrigation water applied in the treatments ranged from 252 (drip) to 351 mm (Table 11).

Irrigation water decreased by 01–28%. Nitrogen applications ranged from 5.7 kg/decare (drip) to 10 kg/decare (sprinkler with granule nitrogen and sprinkler with granule and liquid nitrogen). Nitrogen savings reached up to 43% in drip irrigation.

The average total yield varied between 2757 (Madera, sprinkler with granule and liquid nitrogen) and 3934 kg/decare (Paladine, drip), depending on the year and the treatment (Table 12). Although the highest yield was obtained for both varieties, from drip irrigation with liquid nitrogen, varieties responded differently to nitrogen form and amount.

The total yield of the Madera variety was only 18% less with sprinkler and granule and liquid nitrogen than with drip irrigation and liquid nitrogen. Similarly,

Table 11. Amount of irrigation water and nitrogen and their savings for watermelon.

Treatment	Water (mm)	Nitrogen (kg/decare) [a]	Saving (%)	
			Water	Nitrogen
SG	334	10.0	5.0	0.0
SGL	347	10.0	1.0	0.0
SL	351	5.9	0.0	41.0
DL	252	5.7	28.0	43.0

Source: Şenyiğit (1998).

Note: DL, drip with liquid N; SG, sprinkler with granule N; SGL, sprinkler with granule and liquid N; SL, sprinkler with liquid N.

[a] 1 decare = 0.1 ha.

the yield of the Paladine variety with drip irrigation was 24 and 12% higher than in treatments using sprinkler with liquid nitrogen and sprinkler with granule and liquid nitrogen, respectively. The marketable yields from drip irrigation were also the highest among the treatments. The lowest marketable yields were for the Madera variety with sprinkler and granule and liquid nitrogen at 1867 kg/decare. Decreases in yields varied between 33% (Paladine, sprinkler with liquid nitrogen; and Madera, sprinkler with granule and liquid nitrogen) and 17% (Paladine, sprinkler with granule nitrogen) of those from drip irrigation.

The yield losses and WUE for watermelon with various irrigation methods and nitrogen types are given in Table 13. The yield losses as a proportion of marketable yield showed differences between total and marketable yield of watermelon. The highest loss occurred for Madera with sprinkler and granule and liquid nitrogen, at 32%. The lowest loss was for both varieties with drip irrigation.

Average WUEs ranged 7.16–12.92 kg/decare per mm. WUEs under drip irrigation were higher than under sprinkler irrigation by an average 27% and 29% for Madera and Paladin varieties, respectively. Similarly, values for Madera were 17% higher than those for Paladin under sprinkler irrigation. Yield-response factor was 1.07 for total yield and 1.49 for marketable yield.

Şenyiğit concluded that the effects of irrigation methods and nitrogen levels on some parameters of watermelon are unimportant. But fruit diameter of Madera was larger than that of the Paladin variety, and the longest fruit length was from Paladin with drip irrigation and liquid nitrogen. Şenyiğit therefore determined that nitrogen applied through irrigation water increased watermelon yield. Thus, watermelon yield increased considerably with nitrogen applied through the irrigation water.

Table 12. Total and marketable yield for watermelon varieties and irrigation methods.

	Yield (kg/decare) [a]				Yield (%)			
	Total		Marketable		Total		Marketable	
Treatment	Madera	Paladine	Madera	Paladine	Madera	Paladine	Madera	Paladine
SG	3140	3492	2172	2702	94	89	78	83
SGL	2757	3448	1867	2509	82	88	67	77
SL	2998	3007	2220	2188	90	76	79	67
DL	3343	3934	2796	3253	100	100	100	100

Source: Şenyiğit (1998).

Note: DL, drip with liquid N; SG, sprinkler with granule N; SGL, sprinkler with granule and liquid N; SL, sprinkler with liquid N.

[a] 1 decare = 0.1 ha.

Table 13. Yield losses and WUE.

	Yield loss (%)		WUE (kg/decare [a] per mm)	
Treatment	Madera	Paladine	Madera	Paladine
SG	31	23	9.78	7.56
SGL	32	27	9.67	7.18
SL	26	27	8.85	8.59
DL	16	17	12.92	11.11

Source: Şenyiğit (1998).

Note: DL, drip with liquid N; SG, sprinkler with granule N; SGL, sprinkler with granule and liquid N; SL, sprinkler with liquid N; WUE, water-use efficiency.

[a] 1 decare = 0.1 ha.

Greenhouse experiments

Çevik (1978) conducted the first studies under greenhouse conditions in the Agricultural Engineering Department of the Faculty of Agriculture, Çukurova University. Çevik used a system from the Israel–Netafim firm. The one-way (exit) drippers had a 0.5-bar pressure with 2-L/hour flow rate. The experiments compared three irrigation techniques (minisprinkler, drip, and perforated pipe for tomatoes). Results of the study are presented in Table 14.

As seen in Table 14, the highest yields came from drip and sprinkler irrigation in spring. The autumn results did not show significant differences between the yields.

Çevik et al. (1984) conducted another experiment in a greenhouse to obtain the effects of various soil-mulch and irrigation methods on banana yield in Adana. Some results from this study are presented in Table 15. The researchers showed that bananas can grow without manure as a soil mulch. Banana growers can use volcanic tuff for soil mulching. Abundant water was used in trough irrigation, about three times that of drip irrigation in all the soil-mulch treatments. The highest yields came from farmyard-manure mulch with drip irrigation and the lowest yields came from treatment T_1, with drip irrigation.

Topçu (1988) studied the effects of various irrigation intervals on the yield and quality of peppers *(Capsium annumvar grossum)* grown under protected conditions and drip irrigation. Topçu carried out this study to determine the effect of daily and every-third-day drip irrigation on yield and quality of peppers grown under high plastic tunnels. The results show a significant difference between the

Table 14. Comparison of irrigation techniques for tomato yield.

Period	Method	Texture	Irrigation water (mm)	Yield (kg/decare) [a]	Avg fruit weight (g)	Vitamin C (g/100 mL)	Yield (kg decare^{-1} 100 mm^{-1})
Autumn	Drip	F SL	80	2950	47	5.4	3950
		CL	80	3000	46	8.1	4000
	Sprinkle	F SL	130	2900	49	5.1	2850
		CL	170	2925	46	6.3	1700
	Perforated pipe	F SL	90	3500	45	5.0	4150
		CL	140	3000	45	5.0	2200
Spring	Drip	F SL	250	5500	74	15.6	2250
		CL	250	6400	72	14.7	2250
	Sprinkle	F SL	330	6700	80	12.9	2150
		CL	300	5900	67	13.7	1950
	Perforated pipe	F SL	270	6350	81	15.1	2400
		CL	240	5100	62	14.5	2250

Source: Çevik (1977, 1978).
Note: CL, clay loam; F SL, fine silty loam.
[a] 1 decare = 0.1 ha.

Table 15. Comparison of various mulching and irrigation techniques for greenhouse bananas.

Method	Mulch	Irrigation water (m^3)	Yield (kg)	Yield (kg/m^3 water)	Yield (kg/plant)	Yield (kg/cm^2 stem)	Fruit weight (g)	Fruit length (cm)	Fruit per cm	Sugar (%)
Drip	T_1	2.2	2.8	1.3	3.8	35.3	59.2	14.5	9.8	18.9
	T_2	2.7	11.2	4.1	6.6	37.7	54.6	15.4	9.8	15.2
	T_3	4.2	15.6	3.0	8.4	36.8	70.6	16.7	10.3	16.3
	T_4	2.7	11.9	4.4	7.6	41.4	69.7	14.3	10.5	16.2
Trough	T_1	6.2	9.6	1.6	6.3	31.6	57.4	14.9	9.8	16.0
	T_2	6.2	12.2	2.0	6.1	35.8	55.9	15.3	9.7	16.4
	T_3	6.2	12.8	2.1	6.8	32.4	47.4	14.2	9.3	14.4
	T_4	6.2	10.9	1.8	7.1	37.5	63.3	15.6	10.3	16.5

Source: Çevik et al. (1984).

yields and quality of peppers under the various treatments. Although the differences in quality were not significant, daily irrigation resulted in higher yields. The results obtained from the study are presented in Table 16.

Ercan (1988) studied the effect of various irrigation intervals on the yield, quality, and earliness of eggplants (*Solanum melongena* L.) grown under protected conditions and drip irrigation. Ercan aimed to determine the effect of various irrigation intervals (daily and every third day) on the yield and earliness of the drip-irrigated eggplants grown under high plastic tunnels. This study determined that the effects of daily and every-third-day applications on yield, quality, and earliness of eggplants were significantly different. Daily irrigations resulted in slightly higher yields. In addition, daily applications tended to improve earliness. The results obtained from this study are presented in Table 17.

Oğuzer et al. (1991) carried out a study to determine the effects of various cover materials and trickle irrigation intervals on the yield and quality of green peppers (*Capsicum annuum* var. *Demre Sivri*) grown under high plastic tunnels and Çukurova conditions during the 1988/89 growing season. The results show that the highest yield, 1653 kg/decare, came from the double-cover plastic tunnel with daily irrigation, whereas the yield was 1136 kg/decare from the double-cover, stripe-painted tunnel with daily irrigation. The corresponding yield value for single cover was 819 kg/decare. The effect of various covers on the average 3°C was higher than the others.

The amount of irrigation water applied with daily interval was 216.8 m^3/decare, whereas the corresponding figure for the 3-day interval was 232.1 m^3/decare. Pepper yields between the various irrigation intervals were not significantly different. WUE was highest in the double-cover tunnel with daily irrigation, at 7.35 kg/m^3, whereas the respective figure for the single-cover tunnel with 3-day interval was 2.86 kg/m^3. Vitamin C content was found higher in the double-cover tunnel with daily irrigation than in other treatments.

Çevik et al. (1992) conducted a detailed study covering 2 years to determine the effects of various irrigation levels on the yields, quality, and evapotranspiration of cucumbers grown under glass-house conditions in the Çukurova region. This experiment tested various irrigation levels (20/30 cb and 40/50 cb) and mulching materials (wheat straw, black plastic, clear plastic, and bare soil). The Maram F_1 cucumber cultivar was the test crop. Çevik et al. used a trickle system to apply irrigation water. According to the results of their study, the average value of evapotranspiration of treatments varied 205–253 mm. Generally, the maximum monthly evapotranspiration occurred in May, at rates of 106 mm/month and

Table 16. The effect of various irrigation intervals on the yield and quality of drip-irrigated peppers.

	1986		1987	
	Daily	Every third day	Daily	Every third day
Irrigation water (mm)	421.8	433.0	390.6	403.3
Marketable yield (kg/decare) [a]	517.5	486.6	2927.7	554.5
Yield ((kg/decare per 100 mm)	1226.8	1123.0	749.5	554.5
Weight per pepper (cm)	39.4	40.2	38.0	38.2
Volume per pepper (cm^3)	85.8	84.2	80.4	81.7
Diameter of pepper (cm)	4.87	4.89	5.14	5.17
Height of pepper (cm)	6.46	6.44	5.85	5.98
Vitamin C (mg/100 g)	62.8	59.3	91.8	88.3
Thickness of pepper (cm)	0.28	0.27	0.31	0.30

Source: Topçu (1988).
[a] 1 decare = 0.1 ha.

Table 17. The effect of various irrigation intervals on yield, quality, and earliness of drip-irrigated eggplants.

	1986		1987	
	Daily	Every third day	Daily	Every third day
Irrigation water (mm)	508.8	525.9	601.8	621.7
Marketable yield (kg/decare) [a]	5170.9	4581.3	2947.4	5104.0
Yield per unit of water (kg/m^3)	10.2	8.7	9.9	8.2
Weight per eggplant (g)	130.5	127.5	137.0	134.9
Volume per eggplant (cm^3)	187.2	173.6	192.9	198.3
Height of eggplant (cm)	18.4	18.4	20.3	20.2
Diameter of eggplant (cm)	4.15	4.07	4.41	4.22

Source: Ercan (1988).
[a] 1 decare = 4.05 ha.

3.4 mm/day. The yields from the mulches of black and clear plastic were higher than those from others, whereas yields in trial years were not statistically different. Maximum yield was obtained from treatment M_3S_2, with an average 111.5 t/ha. Fruit length, width, and volumes were changed under effects of application of mulches, whereas there was no important effect on the characteristics of irrigation.

The results of some vegetable experiments are presented in Table 18. They are insufficient to generalize regarding the use of drip irrigation in greenhouses for irrigated crop production in the region. We would need further studies on cucumbers, melons, eggplants, and peppers to determine whether indeed trickle irrigation systems have advantages.

In 1997 and 1998, we carried out an experiment on rose grown under greenhouse conditions. This was to determine the effects of irrigation intervals and nitrogen dosages on the quality and yield of large Sandra hybrid tea rose. The treatments fell into split-plot experimental design with three replications. We considered three nitrogen levels (N_1, 50 kg/ha; N_2, 100 kg/ha; and N_3, 150 kg/ha) and three irrigation intervals (A, 2 days; B, 4 days; and C, 6 days).

At the beginning of the experiment, all plots received an equal amount of irrigation, with further applications at 2-, 4-, and 6-day intervals. The plots in treatments A, B, and C received 47, 25, and 17 irrigations, respectively (Table 19). Treatment A used the highest amount of water (273 mm); and treatment C, the lowest (248 mm).

No significant difference appeared between irrigation water and evapotranspiration in treatments. They varied 248–273 mm. The highest evapotranspiration occurred in treatment BN_2, with 281 mm (Table 20).

Total WUE and irrigation WUE varied from 57.66 (AN_3) to 78.71 (BN_3) and from 55.97 (AN_2) to 78.42 (CN_3) flower/mm per decare, respectively. It was obtained that nitrogen doses have no significant effect on the WUE of rose.

The effects of nitrogen doses and irrigation intervals were statistically significant. The maximum flower number occurred in treatment BN_3 with 359. With this irrigation interval (4 days), all nitrogen dosages increased the numbers of flowers over other irrigation intervals (Figure 13).

Some rose qualities, such as flower number, stem length, stem diameter, sepal diameter, flower length, and flower width, differed either at nitrogen doses, irrigation intervals, and interaction of both. The best result was in treatment BN_3, with a 4-day interval and 150 kg/ha of nitrogen.

The flowers harvested were standardized in terms of the stem length to determine the marketable number of flowers. According to ITC standards, 89% of the total flowers were 60 cm or more in length (Figure 14). However, the ratio varied 87–91%, depending on the treatment. Taking all treatments into consideration, one can argue that the percentages of the marketable numbers of flowers were within the acceptable range. However, the average stem length differed in the months of harvesting. The longest stem length, nearly 80 cm, appeared between December and February for all irrigation intervals.

Table 18. Irrigation water use and yield on different irrigation methods.

Crop	Irrigation method	Irrigation water (mm)	Yield (t/ha)	WUE [a]
Tomato	Drip	80–250	30–64	3.7–2.6
	Sprinkler	130–330	29–67	2.2–2.0
	Perforated pipe	90–270	30–64	3.3–2.4
Pepper	Drip, daily	391–422	29–52	0.7–1.2
	Drip, 3-day interval	403–433	22–49	0.5–1.1
Eggplant	Drip, daily	509–602	52–59	1.0–0.98
	Drip, 3-day interval	526–622	46–51	0.9–0.80
Banana	Drip	984–1528	18.7–22.5	0.2–0.15
	Trough (conventional)	2407–2784	16.2–22.5	0.07–0.08

Note: WUE, water-use efficiency.
[a] WUE = 100 (yield/irrigation water).

Like stem diameter, sepal diameter affects vase life. As is well known, if sepal space is open more on a flower bud, the opening can be fast and thus result in short flower vase life (Keser 1998). The highest sepal diameter appeared in BN_2, with an average 0.925 cm; and the lowest, in CN_3 (Figure 15). The effect of nitrogen dosages was significantly different between irrigation intervals. For instance, the maximum sepal diameter was with N_1 and the 6-day irrigation interval. The sepal-diameter values for the treatment varied during the experimental period. The widest diameters appeared in months after the growing season, such as January and February. In these months, all treatments gave similar results.

The nitrogen content of the leaves differed between treatments (Figure 16). With N_1, the plant tissues contained low nitrogen for all irrigation intervals. With this dosage, the maximum nitrogen content was in A, with 2.62 mg/g, and the minimum of 1.385 mg/g was in B. In all treatments, nitrogen content of plant leaves with N_2 was higher than with N_1 and N_3. Generally, the frequent irrigations increased the nitrogen content of the plant tissue.

Irrigation problems of horticultural crops in the Mediterranean region

The Mediterranean region offers the best climate for almost all kinds of crops. However, the irrigation of crops grown in greenhouses still has problems with

Table 19. Number of irrigations, water amount, and evapotranspiration.

	Treatment [a]								
	A			B			C		
Month	Number of irrigations	IR (mm)	ET (mm)	Number of irrigations	IR (mm)	ET (mm)	Number of irrigations	IR (mm)	ET (mm)
October	3	57	41	2	44	29	2	57	37
November	15	103	98	8	111	110	5	97	100
December	14	51	56	7	75	66	5	29	36
January	15	62	73	8	37	69	5	65	82

Source: Keser (1998).
Note: ET, evapotranspiration; IR, irrigation water.
[a] A, 2-day interval; B, 4-day interval; C 6-day interval; N_1, 50 kg/ha N; N_2, 100 kg/ha N; N_3, 150 kg/ha N.

Table 20. Irrigation water and total WUE.

Treatment [a]	IR (mm)	ET (mm)	Flowers (*n*)	IWUE (flowers/mm per decare) [b]	TWUE (flowers/mm per decare)
AN_1	273	268	283	60.00	61.12
AN_2	273	264	264	55.97	57.88
AN_3	273	270	269	57.03	57.66
BN_1	267	266	347	75.22	75.50
BN_2	267	281	305	66.12	62.82
BN_3	267	264	359	77.82	78.71
CN_1	248	244	288	67.21	68.32
CN_2	248	257	265	61.85	59.68
CN_3	248	254	336	78.42	76.56

Source: Keser (1998).

Note: ET, evapotranspiration; IR, irrigation water; IWUE, irrigation water-use efficiency; TWUE, total water-use efficiency.

[a] A, 2-day interval; B, 4-day interval; C, 6-day interval; N_1, 50 kg/ha N; N_2, 100 kg/ha N; N_3, 150 kg/ha N.

[b] 1 decare = 0.1 ha.

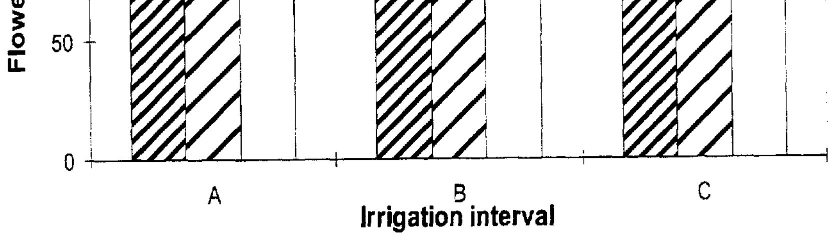

Figure 13. Average number of flowers in treatments. Note: A, 2-day interval; B, 4-day interval; C, 6-day interval; N_1, 50 kg/ha N; N_2, 100 kg/ha N; N_3, 150 kg/ha N. Source: Keser (1998).

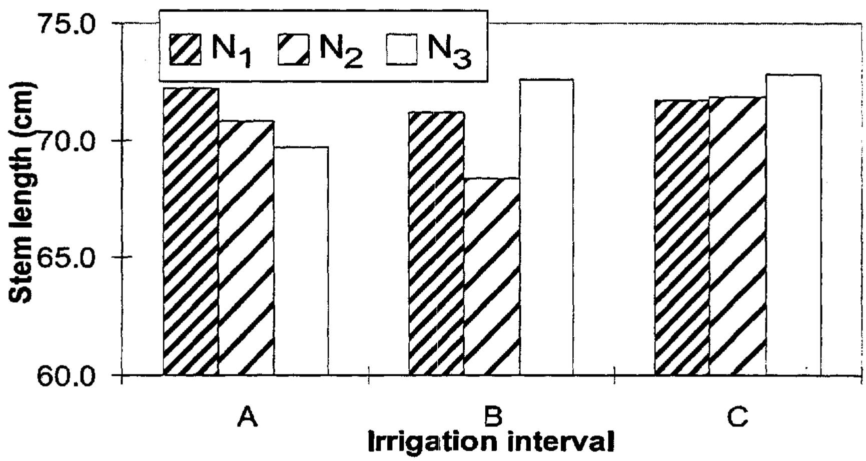

Figure 14. Stem length of marketable flower for treatments. Note: A, 2-day interval; B, 4-day interval; C, 6-day interval; N_1, 50 kg/ha N; N_2, 100 kg/ha N; N_3, 150 kg/ha N. Source: Keser (1998).

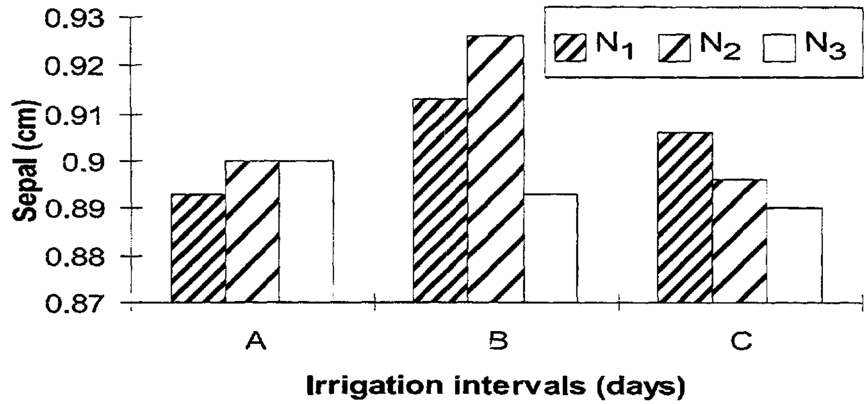

Figure 15. Change of sepal diameter in treatments. Note: A, 2-day interval; B, 4-day interval; C, 6-day interval; N_1, 50 kg/ha N; N_2, 100 kg/ha N; N_3, 150 kg/ha N. Source: Keser (1998).

crop yield and quality. A number of research projects are under way to overcome such problems for vegetable crops:

- Soil-water characteristics and the evaluation of the suitability of irrigation waters;

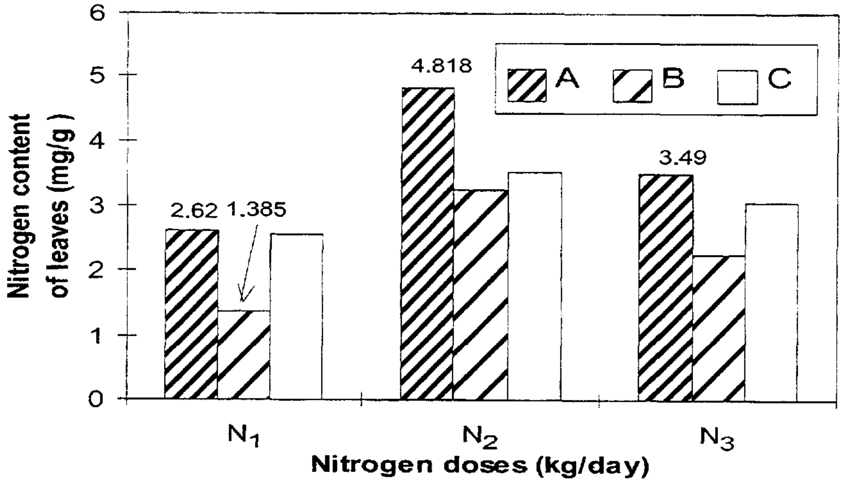

Figure 16. Nitrogen content of plant leaves. Note: A, 2-day interval; B, 4-day interval; C, 6-day interval; N_1, 50 kg/ha N; N_2, 100 kg/ha N; N_3, 150 kg/ha N. Source: Keser (1998).

- Rooting patterns at various growth stages;
- Irrigation timing and the physiological characteristics of crops;
- A suitable method to determine the best time to irrigate to obtain the best and highest yields (tensiometers can be a good tool for determining when to irrigate);
- Evapotranspiration and water requirements of vegetable crops grown in greenhouses;
- Various soil and crop parameters used in designing trickle irrigation systems; and
- Various other parameters of greenhouse drainage systems.

Conclusion

Trickle irrigation is an effective and efficient way to irrigate most plants in low-rainfall areas (like the Mediterranean region). The high frequency, low-volume water applications used in trickle irrigation maintain more favourable soils and plant-water conditions than those in furrow irrigation. Crop yield in the experiments was increased by trickle irrigation. Moreover, trickle-irrigated crops can more effectively use water than those in furrow and sprinkler irrigation. Thus, WUE is high in trickle irrigation. The effect of trickle irrigation on quality of crops yield is also clearly important.

Further, the results of the experiments presented here give some direction in planning a research program on irrigation in Turkey. On the basis of the experiments, a few recommended studies would be as follows:

- Studies of the effects of drip irrigation on other crops of economic importance;
- Studies dealing with response to irrigation application; and
- Priority should be given to experimental studies carried out in greenhouses to develop recommendations on dealing with soil, climate, and diverse agricultural practices.

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Chapter 3

Drip Irrigation in Northern Cyprus

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Introduction

In arid and semi-arid regions, irrigation is an inseparable part of adequate crop production and is generally defined as putting some part of plant water requirements not covered by precipitation into the plant root zone. Irrigation is also one of the most important agricultural inputs, and it increases the effectiveness of other inputs. To make optimal use of water resources, contribute to sustainable agriculture, and decrease or eliminate the negative effects of irrigation on the environment, the main principle of irrigation is to apply only the water a plant needs for optimal use and to apply it at the best time, at the best place (where active roots are) and with minimal water loss. Growers therefore need to know their irrigation water requirements, the application time, and location well, to determine the most economical amount of water and frequency of application and to devise and use the best irrigation technology.

Successful irrigation of agricultural lands depends on selecting the most suitable irrigation method for the climate, water resources, soil, topography, plants, economic conditions, and farmer requirements. It requires planning and designing the irrigation system needed for this method and installing and operating of the system in accordance with these characteristics of the agricultural land. Moreover, evaluation and monitoring should be part of the operation phase of the system to eliminate existing errors and collect data to help install new irrigation systems around the region.

Efficient irrigation directs water to a plant's active root system with maximum efficiency, and the best and newest method is drip irrigation. Conventional irrigation practices, such as surface or sprinkler methods, only partially achieve desired results.

Drip irrigation

The main principle of drip irrigation is to introduce water into the soil where plant roots grow most intensively and to introduce it at the right time and rate (Goldberg et al. 1976; Nir 1982). For this purpose, farmers place pressurized pipelines, termed "lateral lines," along the plant rows and fit emitters with a discharge rate of few litres per hour at nearly zero (atmospheric) pressure at certain points along these lines. Water generally leaves the emitters at the specific points over the soil surface. After the water infiltrates the soil, it spreads laterally and vertically inside the soil to a limited extent and wets only that fraction of the soil where plant roots effectively grow up. Drip irrigation applies water frequently at very low rates to achieve low moisture stress and optimum plant growth (Karmeli and Keller 1975; Burt and Stuart 1994; Yıldırım and Korukcu 2000).

In drip irrigation, when planning and operation are good, no surface flow or delivery losses occur, as the water moves from source to emitter through pressurized pipes to certain points on the soil surface at a very low rate. With drip irrigation, evaporation losses and deep percolation are also very low, and thus it achieves very high irrigation efficiency and uses water very effectively (Baars 1976; Nakayama and Bucks 1986).

Irrigation water goes to lateral lines only after acquiring suspended plant nutritional elements. A control unit controls discharge rate and operating pressure, and the system efficiently meets plant nutritional requirements in the right amount and at the best time (Golberg et al. 1976; Nir 1982; Burt and Stuart 1994).

We discuss some advantages of drip irrigation over surface and sprinkler methods, below.

With drip irrigation, water losses as a result of evaporation from soil surface, surface runoff, or deep percolation, are minimal because drip irrigation applies irrigation water more efficiently, applying it at slow rates and to limited areas. This provides better uniformity and higher irrigation efficiency. Growers' irrigation water requirements are therefore low, and they can irrigate larger areas of agricultural land using their current water resources.

Drip irrigation generally achieves higher and better quality crop yields, soil moisture in the active root zone continuously at an optimum level, introduces fertilizers effectively into the root zone with the irrigation water, and regulates their rate and composition to meet the plant's requirements, with high availability and few losses.

Farmers can safely grow plants sensitive to soil salinity under conditions of saline soil or water, as the frequent water applications dilute the salts in the soil water more and leach them to the perimeter of the wetted soil volume. Labour costs are lower, as water control and work are easy and require fewer human resources. Weed growth is reduced because drip irrigation wets only certain parts of the soil surface, and plant diseases and pests are rare, as it does not wet plant leaves.

With good planning and operation, growers can use drip irrigation where they would be ill-advised to use surface irrigation, such as under conditions of high land slope, undulating topography, soils with low available water-holding capacity, and shallow soils. Drip irrigation is also useful for crops sensitive to diseases resulting from wetted leaves, which farmers cannot generally use the sprinkler method to irrigate.

Drip irrigation has few negative effects on the environment because it rarely creates problem such as drainage, surface runoff, soil erosion, deep percolation, or fertilizer leaching (Nir 1982; Yıldınum and Korukcu 2000).

Some disadvantages are also attached to drip irrigation. We discuss some of these disadvantages and some solutions to them, below.

The main problem with drip irrigation is clogging of emitters with suspended organic materials and chemical precipitation. To prevent or, to a large extent, solve this problem, farmers should filter water very well, using hydro cyclones, gravel filters, and screen filters at the control unit; and they should wash the system with deluted acids and flush the pipelines at certain times during the season.

The cost of a drip irrigation system is very high because it generally contains a lot of heavy materials and complex controls. But for plants with high soil moisture requirements, the high yields with high market values in most cases pay for the high system costs. Particularly under conditions of limited water resources, drip irrigation can be more economical than conventional irrigation systems, as drip irrigation can cover a larger area. In addition, labour and total operating costs are generally lower.

Another problem with drip irrigation is the accumulation of salts at the perimeter of wetted soil volume, particularly near the surface. When more than 300 mm of total rainfall occurs before the irrigation season, it generally leaches these salts. Otherwise, farmers need leaching water, and they generally use a portable sprinkler system for leaching (Nir 1982; Sourel and Schon 1983; Yıldınm 1994; Yıldınm and Korukcu 2000).

In conclusion, growers can use drip irrigation in all soils and topographic conditions and particularly for vegetables, vineyards, fruit trees, and covered crops. It can be economical to use on some crops when water resources are limited or irrigation water is fairly costly (Yıldınm and Korukcu 2000).

Experiences of drip irrigation in northern Cyprus and the Güzelyurt region

Potential of soil and water resources

As shown in full detail in Tables 1, 2, and 3, northern Cyprus has 187 069 ha of agricultural land, of which 113 547 ha is under cultivation, with 104 483 ha being rainfed and only 9059 ha being irrigated, according to data collected in 1997. The Güzelyurt region has 6334 ha (69.92%) of cultivated land under irrigation. In addition, citrus areas are 70.24% (6363 ha) irrigated in northern Cyprus and 84.37% (5344 ha) in Güzelyurt. In other words, citrus areas constitute the largest part of irrigated land in northern Cyprus, and the most important citrus areas (83.99%) are in Güzelyurt (MAF 1998).

As shown in Tables 4 and 5, northern Cyprus has about 117.5×10^6 m^3/year of potential water resources, and most of these are groundwater resources (89.1×10^6 m^3/year, 75.83%). Güzelyurt has 59.5×10^6 m^3/year of groundwater (it is 66.78% of total groundwater and 50.64% of the total water resources of northern Cyprus) (Öztürk 1995). In other words, the aquifers in Güzelyurt are very important to northern Cyprus.

Northern Cyprus uses 97.6×10^6 m^3/year of its water for irrigation and 18.8×10^6 m^3/year for domestic purposes. This means that it has used water in excess of its potential resources, particularly water pumped from its aquifers (Table 5). Thus, problems such as lowering groundwater levels, saline water entering from the sea into some aquifers, and salinization of groundwater have gradually increased. These problems are more evident in Güzelyurt.

Table 1. Land distribution in northern Cyprus.

Land use	Area (ha)	Proportion (%)
Agricultural land	187 069	56.71
Cultivated	113 542	34.42
Uncultivated	73 527	22.29
Forest	64 323	19.50
Grassland	16 345	4.95
Settlements	35 252	10.69
Unused land	26 902	8.15

Source: MAF (1998).

Table 2. Use of cultivated land in northern Cyprus.

Land use	Rainfed		Irrigated		Total	
	ha	%	ha	%	ha	%
Fallow	9 720	8.56	—	—	9 720	8.56
Field crops	88 444	77.90	796	0.70	89 240	78.60
Vegetables	—	—	913	0.80	913	0.80
Citrus	—	—	6 363	5.59	6 363	5.59
Grape and grape-like fruits	6 000	5.28	580	0.51	6 580	5.79
Other fruit trees	318	0.28	321	0.29	639	0.57
Greenhouses and tunnels	—	—	105	0.09	105	0.09

Source: MAF (1998).

Table 3. Use of cultivated land other than fallow in Güzelyurt region.

	Rainfed		Irrigated		Total	
Land use	ha	%	ha	%	ha	%
Field crops	1334 [a]	17.34	541 [a]	7.03	1875	24.37
Vegetables	—	—	299	3.89	299	3.89
Citrus	—	—	5 344	69.46	5344	69.46
Grape and grape-like fruits	26 [a]	0.34	78 [a]	1.01	104	1.35
Other fruit trees	—	—	51 [a]	0.66	51	0.66
Greenhouses and tunnels	—	—	21	0.27	21	0.27

Source: MAF (1998).
[a] Estimated amount.

Table 4. The potential of water resources and their use in northern Cyprus.

Kind of water resource	Potential (10^6 m^3/year)	Irrigation water (10^6 m^3/year)	Domestic water (10^6 m^3/year)
Springs	1.4	0.6	0.8
Streams	27.0	13.0	—
Aquifers	89.1	84.0 [a]	18.0 [a]

Source: MAF (1998).
[a] Excess water is pumped from aquifers.

Table 5. Use of aquifers in northern Cyprus and Güzelyurt region.

Region	Feeding (10^6 m^3/year)	Safe to pump (10^6 m^3/year)	Actually pumping (10^6 m^3/year)	Difference (10^6 m^3/year)
Northern Cyprus	89.1	74.1	103.0	−28.9
Güzelyurt	59.5	44.5	64.5	−20.0

Source: MAF (1998).

Existing irrigation methods and those being considered

Using data collected in 1997, Table 6 summarizes the various methods used to irrigate agricultural land in northern Cyprus and the Güzelyurt region. As the table shows, 88.63% of irrigated land in northern Cyprus and 96.84% of that in Güzelyurt is irrigated using surface methods, more exactly, flooding, which has very high water losses (MAF 1998).

Until 1997, Güzelyurt had installed drip irrigation on 101 ha and 25 ha only of citrus area.

Northern Cyprus and Güzelyurt have potential water resources available for irrigation of 61.7×10^6 m^3/year and 38.5×10^6 m^3/year, respectively (Table 7). If existing irrigation water applications continue, northern Cyprus will have to have 144×10^6 m^3/year in and Güzelyurt will have to have 110×10^6 m^3/year to achieve adequate crop water consumption (Table 7). Water available for irrigation (61.7×10^6 m^3/year) is far from enough to cover these requirements.

Now, for the most part, irrigated land receives limited water, although this has meant pumping 97.6×10^6 m^3/year of excess water from aquifers (Table 4). For example, most Güzelyurt farmers irrigate their citrus orchards only a few times during the season to prevent the trees wilting. As a result, they obtain very low fruit yield and quality.

Table 6. Existing irrigation methods in northern Cyprus and the Güzelyurt region.

	Northern Cyprus		Güzelyurt	
Irrigation method	ha	%	ha	%
Surface	8029	88.63	5767	96.84
Sprinkler	494	5.45	87	1.46
Drip	536	5.92	101	1.70

Source: MAF (1998).

Table 7. Potential water resources for irrigation and water requirements for various uses in northern Cyprus and Güzelyurt region.

Irrigation use	Region	Potential water resources for irrigation (10^6 m^3/year)	Irrigation water requirements (10^6 m^3/year)
	Northern Cyprus	61.7	
	Güzelyurt	38.5	
To continue existing water applications	Northern Cyprus total		144
	Northern Cyprus citrus		102
	Güzelyurt total		110
	Güzelyurt citrus		93
To use drip to irrigate fruit trees and vegetables and sprinkler methods for some field crops	Northern Cyprus total		73
	Northern Cyprus citrus		51
	Güzelyurt total		52
	Güzelyurt citrus		44

Source: MAF (1998).

To make optimal use of water resources in northern Cyprus, farmers must stop using only surface irrigation and immediately start using techniques with low irrigation water requirements and high efficiency. For example, if farmers started to use drip to irrigate citrus and other fruit trees, vegetables, and crops grown in greenhouses or tunnels and sprinkler methods for some field crops, then irrigation water requirements in northern Cyprus and Güzelyurt would be 73×10^6 m^3/year and 52×10^6 m^3/year, respectively, and irrigation water requirements in citrus areas would decrease from 102×10^6 m^3/year to 51×10^6 m^3/year in northern Cyprus and from 93×10^6 m^3/year to 44×10^6 m^3/year in Güzeltyurt (Table 7).

Thus, they would save 24.6 × 10^6 m^3/year of water and also obtain higher crop yield and quality, as they would use adequate amounts of water, rather than continuing with limited water applications. But even with improved irrigation systems and more precise applications, northern Cyprus's (73 × 10^6 m^3/year) irrigation water requirements would exceed its 61.7 × 10^6 m^3/year of water available for irrigation. Thus, it would have to either reduce the area of its irrigated land by about 8% or transport nearly 12 × 10^6 m^3/year of water from abroad. If northern Cyprus took these measures, moreover, this would reduce its pumping of excess water from aquifers and prevent the salinization of groundwater from seawater intrusion.

Modernization project for irrigation systems in the Güzelyurt region

The Ministry of Agriculture and Forestry (MAF) in northern Cyprus has considered all the problems discussed above and has begun a project called the Modernization of Irrigation Systems. Starting with about 1400 ha of citrus orchards in Güzelyurt where water resources are very scarce, MAF has designed the project to install large-scale drip irrigation systems to replace existing surface irrigation. The plan is for MAF to construct water distribution systems for farmers and to install the drip systems in orchards. In addition, some of the farmers who have their own wells have been installing drip irrigation systems with MAF grants to cover part of the system costs (about 40%).

The project has chosen a pilot area comprising 180 ha of citrus orchard, dug two new deep wells, and planned, designed, installed, and begun to operate two drip irrigation systems in this area. The government has supported all system costs to assist the farmers in the region. In addition, the project has completed the design of drip systems covering 600 ha of citrus area and has begun work to install and operate these systems.

All of this work has begun to give results. Between 1997 and 2000, citrus areas where the government or farmers installed drip irrigation systems increased to about 1300 ha in Güzelyurt.

Conclusion

To make optimal use of very limited water resources, northern Cyprus should give up existing surface irrigation and begin to use modern irrigation techniques, such as drip irrigation, and it should immediately expand the modernization project for irrigation systems from a small part of the Güzelyurt region to all the irrigated land in northern Cyprus.

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Chapter 4

POOR-MANAGEMENT IMPACTS ON GÜZELYURT AQUIFER

Mustafa E. Ergil

Introduction

People generally regard groundwater as a renewable natural resource. This is only true if the recharge and discharge components of the aquifer in a basin are balanced. Hence, with regulation of inflow and outflow from the basin, an underground reservoir can function beneficially for a very long time. But extracting water for irrigation above the safe-yield capacity of a coastal aquifer can cause seawater intrusion, which has been one of the most serious water contamination problems of the last few decades.

To overcome this, we need to establish the rate at which we can, under certain conditions, withdraw water perennially without producing undesirable results. Otherwise, the unavoidable consequences will be the progressive reduction of the groundwater resource, uneconomic conditions for pumping, and degradation of water quality. Such mismanagement of a groundwater basin depletes the aquifer, and this is why groundwater levels have shown excessive declines, extending even below mean sea level, where the sensitive balance between fresh- and saltwater bodies on the coastline changes (Mull et al. 1980; Reilly et al. 1985).

Water is a more precious commodity in northern Cyprus than in most other places. Water scarcity in Cyprus has become a vital issue particularly considering its potential effects on the social and economic development of the island. The water problem in northern Cyprus seriously impedes economic growth, as about 90% of water supply currently goes to irrigation.

The problem of seawater intrusion has occurred in both of the coastal aquifers of northern Cyprus, Gazimağusa in the east and Güzelyurt in the west, in 1958 and 1967, respectively, and it increased the annual cost of crop production because of the increasing salinity of irrigation water and the extra (annual) pumping costs resulting from declining water tables. Seawater has so thoroughly contaminated the Gazimağusa coastal aquifer that it is now completely out of use.

This study investigated the Güzelyurt aquifer to better understand the phenomenon of seawater intrusion. It correlated and coupled the available water-head level contours and their appropriate sodium chloride (NaCl)–iso-chloride lines with the amount of effective precipitation and the water required for irrigation and for other municipal needs in the area. It offered an opportunity to estimate the monthly amount of direct seawater interfering with and contaminating the coastal aquifer, using the volumetric (3-d) approach of the water-budget equation, and to thereby interpret the effect of seawater encroachment occurring along the coast of Güzelyurt Bay.

Description of the site

Location

Cyprus is an island in the eastern Mediterranean sea, with an area of 9250 km^2. It has two administrative areas, northern and southern Cyprus. The Güzelyurt aquifer (lat. 35°20′N, long. 33°15′E) is the northern part of the island's largest and most valuable groundwater reservoir (Figure 1).

Climate

Cyprus is a semi-arid island, with a Mediterranean climate of hot, dry summers and cool, wet winters. Temperatures occasionally rise above 40°C in summer and rarely fall below zero in winter. Rainfall only occurs between late October and early April, with a 20-year average annual rainfall of 280 mm above the aquifer (the 50-year average is 320 mm) (Figure 2). So the yearly average value seems to be dropping continuously, as a result of ecological changes and long dry periods. Essentially, most of the runoff occurs during winter. Hence, no perennial stream discharges into the sea, either in the study area or anywhere on the entire island. The runoff in the area comes from rainfall and the snowmelt from the uplands of the Troodos Mountains, which have a maximum altitude of 2000 m. After March, when the runoff from snowmelt has dissipated, the stream-flow rates decrease rapidly. Some runoff may come from thunderstorms in the uplands, but not very much from the rare summer precipitation.

Topography and hydrogeology

The Güzelyurt plain is topographically a slightly sloping coastal plain. The land surface in the central part, where agriculture mainly occurs, has an almost flat topography. The elevated hills rise from the northeast to the southwest (Figure 3). In fact, the elevation of the superficial catchment area ranges from sea level along the coast to around 300 m in the northeast and 400 m in the southwest of the Troodos Mountains. The average elevation is around 65 m asl. The land-surface slopes are gentle, except for the fairly high areas, and the gradient is about 1%.

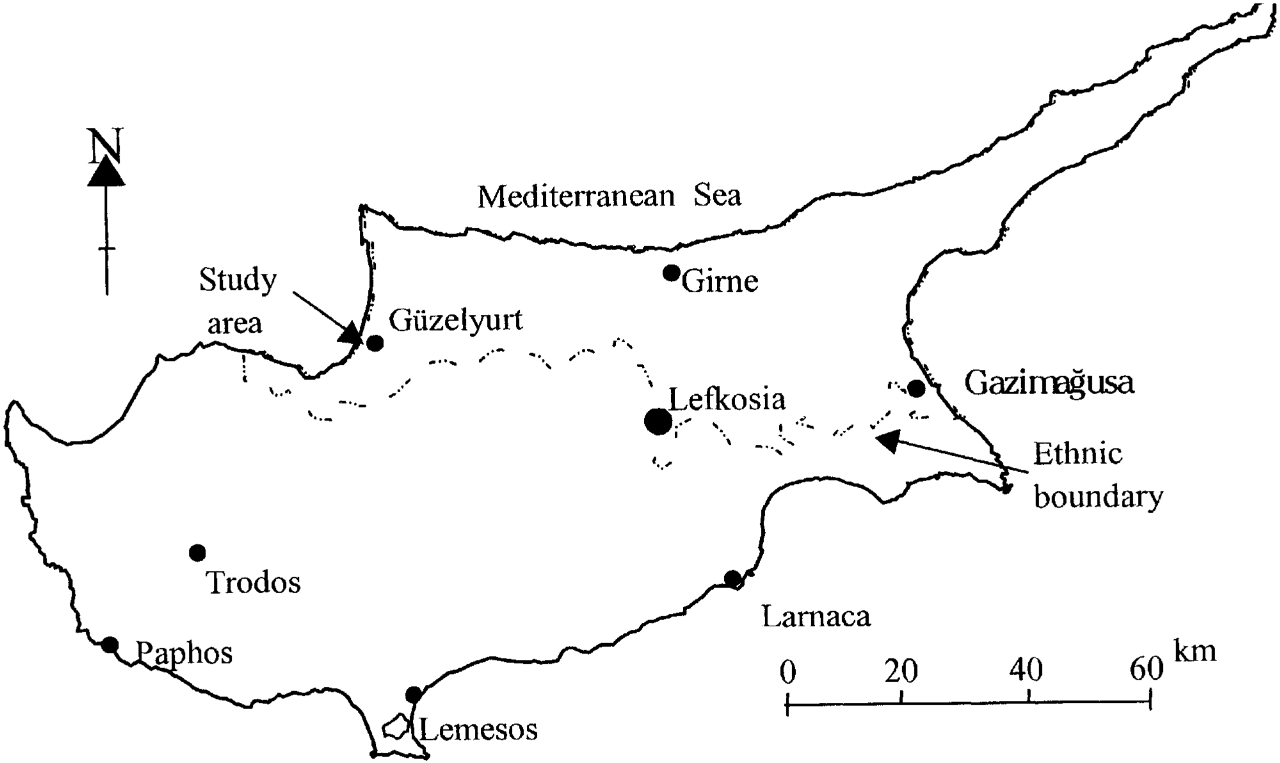

Figure 1. Location of the study area.

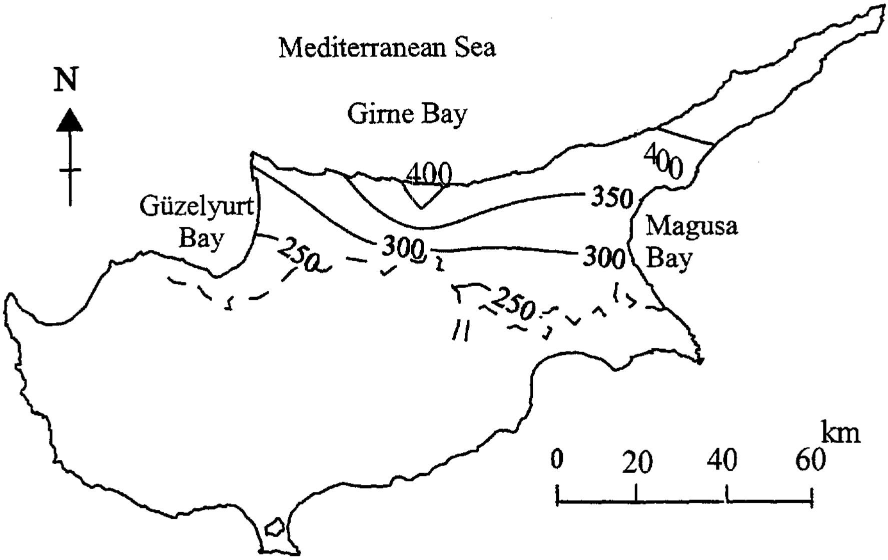

Figure 2. Twenty-year average precipitation over northern Cyprus (mm), 1978–98.

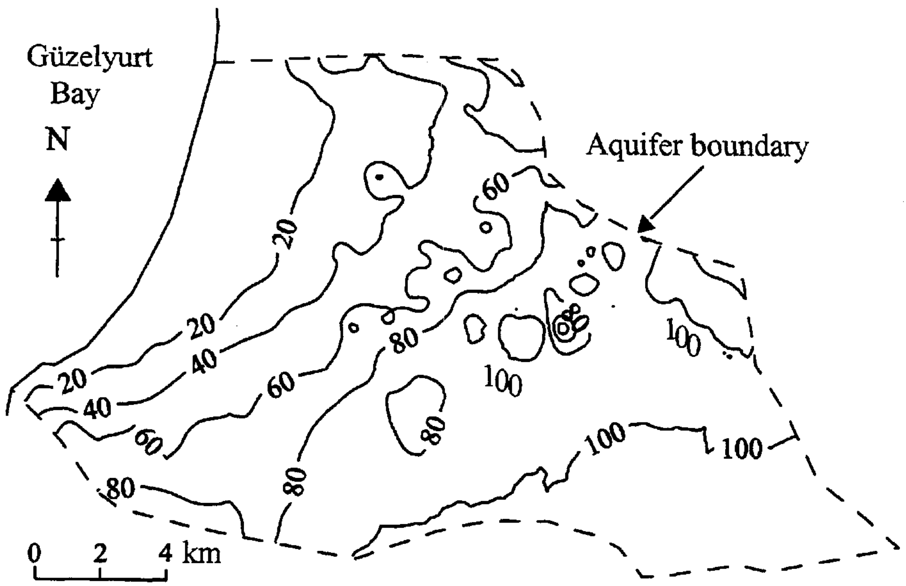

Figure 3. Topographic map of the area of the Güzelyurt aquifer (m asl).

The unfractured, unconfined aquifer is in direct contact with the sea. It comprises gravel, sand, and calcareous sandstone, with intercalations of silt and clay layers and lenses, showing abrupt vertical and lateral variations. The aquifer rests on an impervious base formed by gently undulating Pliocene marls and thick clay. Its thickness ranges from 45 m at the far eastern side to 100 m at the far western side. The thicker side is in direct contact with the coastline along Güzelyurt Bay and is totally under the mean sea level. In the Güzelyurt basin, the groundwater occurs under unconfined aquifer conditions within the superficial deposits and the fanglomerates. The basin has a typical dendritic drainage pattern comprising alluvium, talus, beach, slope wash, river-terrace deposits, and windblown sands, with various proportions of gravels, sands, silts, and clay. The low-lying region of the aquifer at its northwestern side (that is, the one in direct contact with the sea) rests on marl and sandstone, which are highly susceptible to erosion. The coastline is about 12 km long and comprises, in various proportions, sand, gravel, and pebbles (Figure 4) (Electro-Watt 1973).

Citrus fruit plantations are abundant over the study area. The area has five major streams, with the watersheds of Çiftlik and Dar lying to the north and flowing from west to east and the main parts of the watersheds of Güzelyurt, Doğancı, and Çakıl lying in the south and flowing from the upper reaches of the Troodos Mountains in the south, northwest to the sea at Güzelyurt Bay. Several creeks are also developed in the central part of the study area. The study area has three dams, Güzelyurt, Yuvacık, and Şahinler, constructed between 1965 and 1970 for infiltration and irrigation. But the aquifer's recharge is questionable, owing to deposits of fine sediments.

As no one exploits the entire catchment of 460 km^2, the transmissivity, porosity, and specific yield measurements of the region were not available, except for some parts of the heavily planted area. With the guidance and auditing of the Mining Investigation Search Office of Turkey, the Geology and Mining Department supervises the wells (more than 250) opened in the last 20 years over the planted area in the north. The Department estimated the effective porosity (η) of the aquifer through those wells at 15% (MISO 1997).

Importance of the site

The Güzelyurt aquifer is the largest and the most important water reservoir in northern Cyprus, where it contributes substantially to the national economy. Its agricultural products (mainly citrus fruits) generate about 80% of all foreign-currency income resulting from exports. The total area planted in citrus fruit over

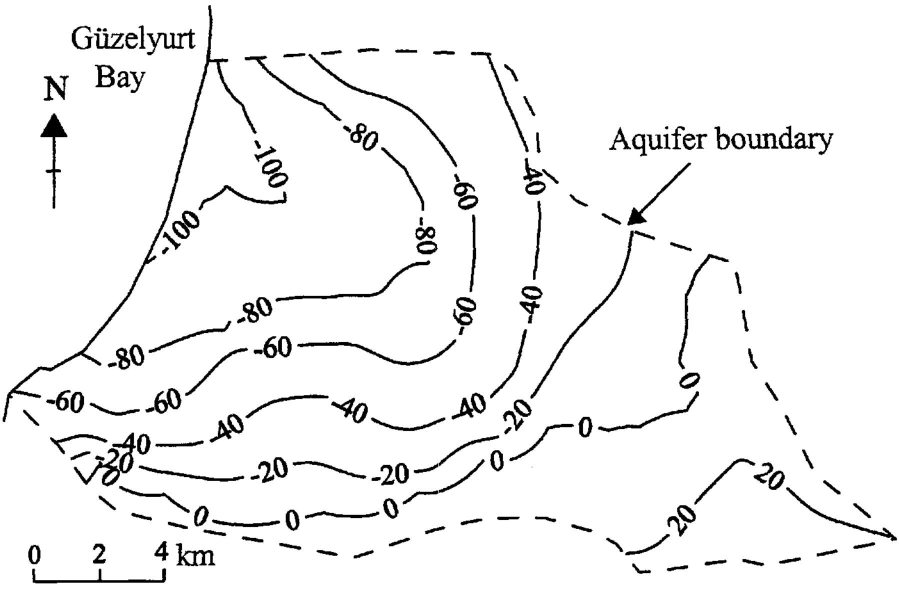

Figure 4. The estimated base of the Güzelyurt aquifer (m asl).

the north in 1975 was about 9900 ha, of which 7400 ha (75%) was in the Güzelyurt area. For this reason more than 2400 wells (scattered all over the plain) have been dug in the Güzelyurt plain at various times since 1950.

The excessive pumping of groundwater from the coastal aquifer, which is used for irrigation and municipal needs, has caused the groundwater level to steadily decline within the study area since 1967, in parallel with increases both in population density and planting-surface area. The natural water table in the northeast has so changed that it is now lower than sea level, thus giving rise to seawater intrusion (Figures 5 and 6).

The water-table level is now 60 m below mean sea level, and the mixing (transition) zone is moving inward and contaminating the aquifer. Recently, up to 3 km inland, the NaCl concentration was above 5000 ppm in some areas (Figures 7 and 8).

Landowners control all the wells in use for irrigation. There are no meters; however, except for a few days for maintenance, the wells are in use nonstop during the irrigation season, from late April to early October. Only 12 wells serve the needs of the municipalities, and with their meters recently installed the government controls these wells. All these wells are in use nonstop throughout the year. Hence, the total amount of water extracted from the aquifer cannot be calculated directly.

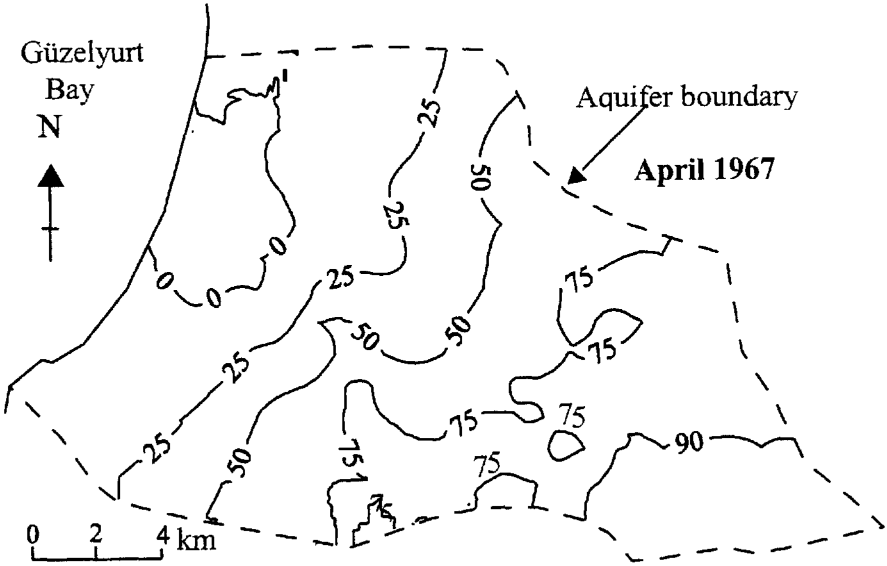

Figure 5. Water-table contours of the Güzelyurt aquifer, April 1967 (m).

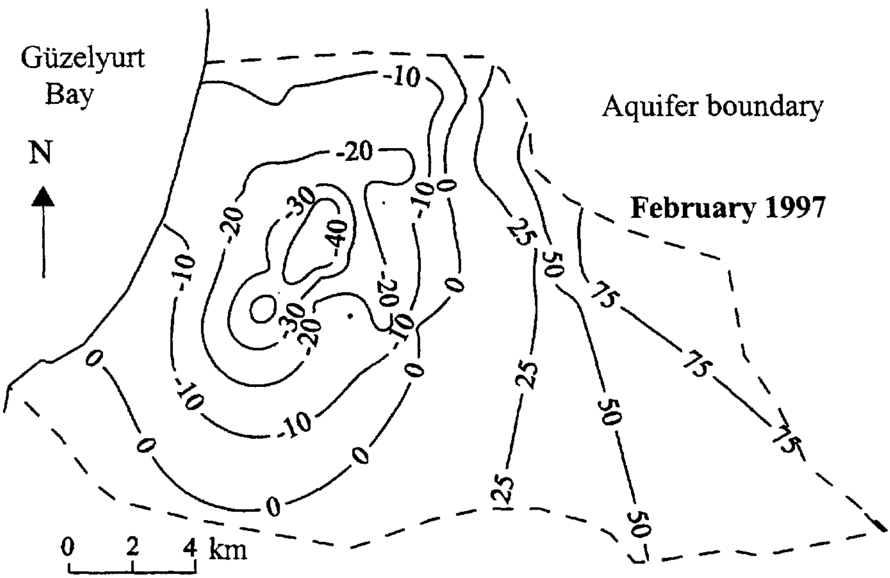

Figure 6. Water-table contours of the Güzelyurt aquifer, February 1997 (m).

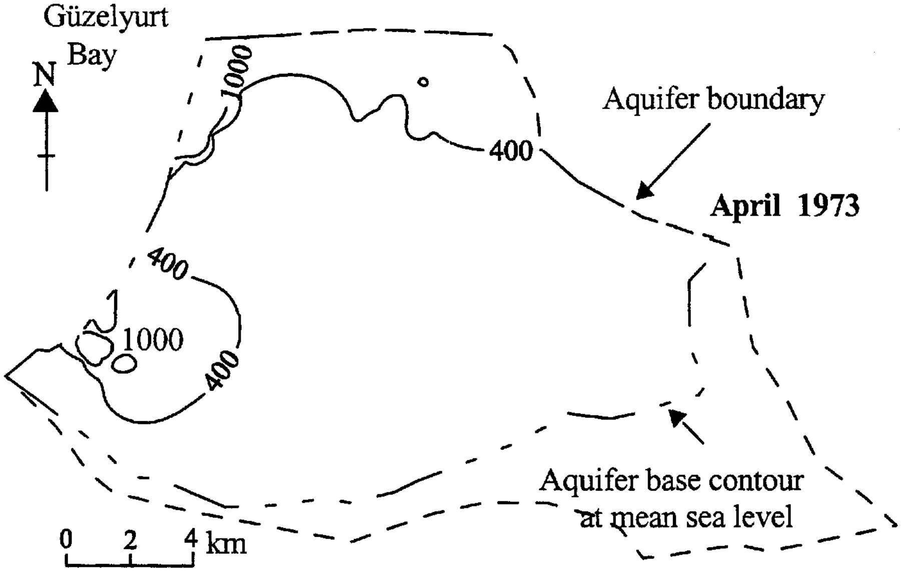

Figure 7. NaCl contours of the Güzelyurt aquifer, April 1973 (ppm).

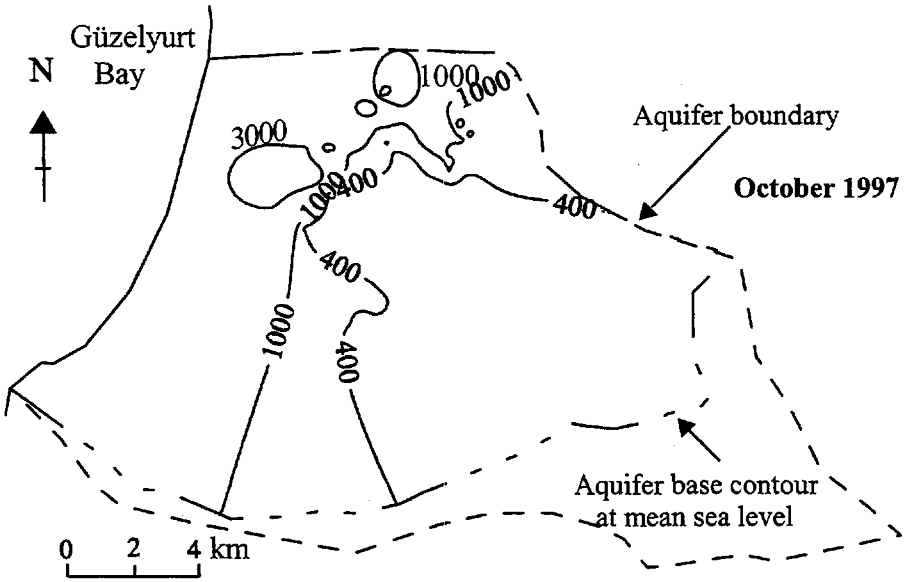

Figure 8. NaCl contours of the Güzelyurt aquifer, October 1997 (ppm).

Of the 650 available wells, the study selected nearly 90 (including the municipal wells) to represent the whole area under investigation — all from different locations of the northern portion of the aquifer, as no information was available from the south, for political reasons (Figure 9).

Analysis of groundwater samples from the observation wells in the study area revealed that the water-level heads at those points and the total NaCl concentration were interrelated. The average background chloride concentration of natural groundwater (obtained from various wells at various locations through the chemical analysis) was about 270 ppm, but, because of the density of the planting in the area and long-term, excessive irrigation, soil salination has occurred, which affects the chloride concentration of the rainwater infiltrating through the recharge (Hamdan et al. 1991; Swain 1997).

The functioning wells over the aquifer fall into four groups (Figure 10), depending on their location and pumping rates:

1. One group of wells, at the inner core of the aquifer, have impervious-bottom levels above mean sea level, making it impossible to pump saline water, as the intrusion has no effect. If the water drawn is above safe yield capacity, the groundwater level drops and merely limits the efficiency of the well.

2. A group of wells have the bottom layer below mean sea level but are situated far from the coast. If the water drawn is greater than the total replenishment, salination may occur after a long time, depending on the aquifer and its exploitation.

3. A group of wells is located near the seashore, where natural replenishment is less than the water drawn. The salination may start earlier than in the wells of group 2, where even the upcoming of seawater may cause salination. Well users may reduce pumping to overcome the problem to some extent.

4. Another group of wells is located very near the coast and just above the saltwater wedge. As a result of the hydrodynamic equilibrium, salination from upcoming definitely occurs, rendering wells in this group useless in a very short time.

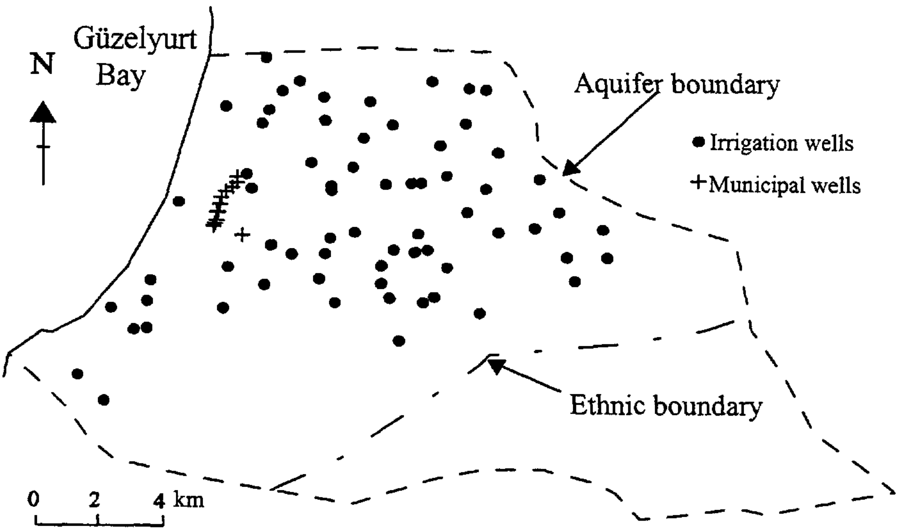

Figure 9. Areal distribution of sample wells.

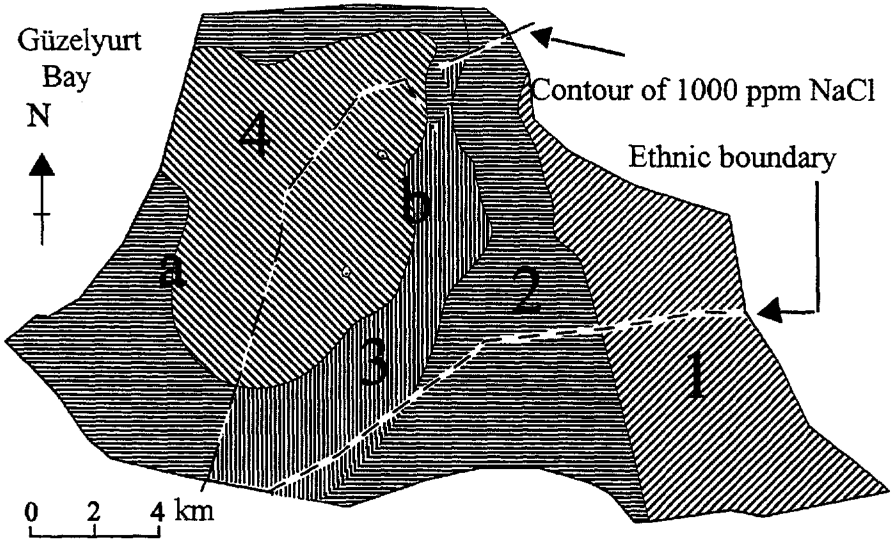

Figure 10. Well groups in the study area and their pumping rates and their NaCl concentrations.

Water potential

The political division of the island, for ethnic reasons, unfortunately divides the study area as well. The superficial catchment area of the aquifer is about 460 km^2 and lies from the Troodos Mountains in the south to Güzelyurt Bay; only 180 km^2 is under the control of the ethnic group in the north. The surface area of the unconfined aquifer occupies 275 km^2, and only 65% is in the north. Because of topography, the recharge occurs mainly from southwest to northeast under normal conditions, but the geologic formations occurring within the area have played an important role in shaping the drainage system, which lies partly outside the aquifer boundary. Over the catchment, the recharge comprises mainly rain but also melting snow from the Troodos Mountains from nearby catchments and water from some semiperennial springs running from south to north during the rainy months. Because of the climate, the drainage system is effective for a few months in the winter, and even flooding occurs, particularly after the heavy rain, in the upper reaches of all the main tributaries of the Güzelyurt and Doğancı rivers in the south. Infiltration decreases the amount of flow within the rivers as they approach the sea.

The people in the area have built or are still building several earthen dams on these rivers at their upper reaches in the south. For political reasons, no appropriate official information is available about their construction and use. Hence, the total amount of water used in the southern part of the aquifer is unknown, but this aquifer might be supplying the municipal water needs of the south.

Spontaneous irrigation from some 30% conveyance losses occurs over about 85% of the area with good quality soil and citrus fruit. The water-table level beneath the irrigation zone is more than 50 m from the surface, in some areas as much as 120 m (that is, more than 70 m below mean sea level). One must therefore discount the seepage of irrigation water, as a result of deep water-table level and high evapotranspiration rate.

In a cross section of the aquifer nearly perpendicular to the coastline, in a direction expected to be representative of seawater intrusion, yearly fluctuation of the groundwater table occurs as shown in Figure 11.

Water budget

The water budget of the study area has two components: the inflow and the outflow. The main input is the infiltration from precipitation. Because no appropriate infiltration measurements were available for the study area, the study used the Thornthwaite method to calculate potential evapotranspiration rates for each month.

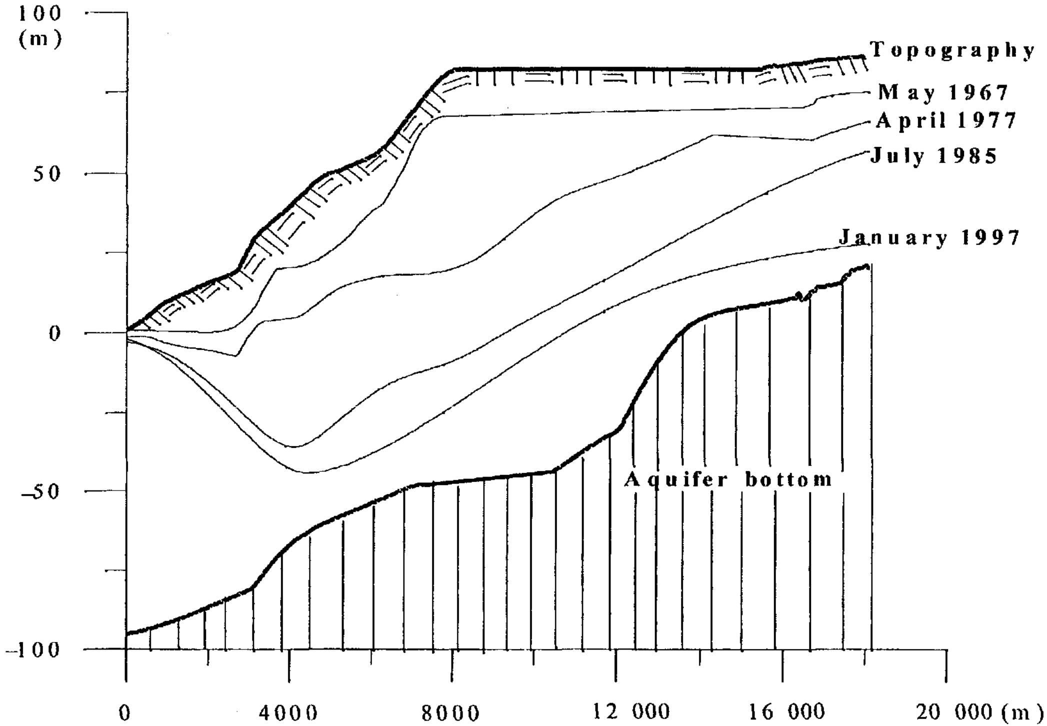

Figure 11. Groundwater fluctuation along a cross section of the aquifer at various times.

The other component of inflow is the estimated monthly intrusion of seawater. Chemical analyses determined the salt concentration results for the wells under investigation.

The main outflow component is the water used for irrigation. Considering the type of plantation, the study used the Blanney-Criddle method to calculate monthly water-use requirements. Wild irrigation is widespread, the conveyance loss of 30% is estimated and the total amount of water pumped for irrigation determined. Note that the drinking water for the cities of Güzelyurt, Lefkoşia, and Gazimağusa, which is nearly 4×10^6 m^3/year, also comes from this aquifer. The study used the mass-balance equation, equation [1], to determine the other component of output, the water used in the south:

$$V_{ppt}\Big|_t + V_{der}\Big|_t + V_{sea}\Big|_{t+2} - V_{irr}\Big|_{t+2} - V_{dri}\Big|_{t+2} - V_{sou}\Big|_{t+2} = V_{avl}\Big|_{t+2} \qquad [1]$$

where

$V_{ppt}\Big|_t$ is volume of water infiltration from effective precipitation at time t (m^3);

$V_{der}\Big|_t$ is volume of water infiltration from the derivation canal at time t (m^3);

$V_{sea}\Big|_{t+2}$ is volume of seawater invading the aquifer at time $t + 2$ (m^3);

$V_{irr}\Big|_{t+2}$ is volume of water extracted from the aquifer for irrigation at time $t + 2$ (m^3);

$V_{dri}\Big|_{t+2}$ is volume of water pumped from the aquifer for drinking at time $t + 2$ (m^3);

$V_{sou}\Big|_{t+2}$ is volume of water used in the south at time $t + 2$ (m^3); and

$V_{avl}\Big|_{t+2}$ is volume of water available in the aquifer at time $t + 2$ (m^3).

Figure 12 shows a diagram for this equation.

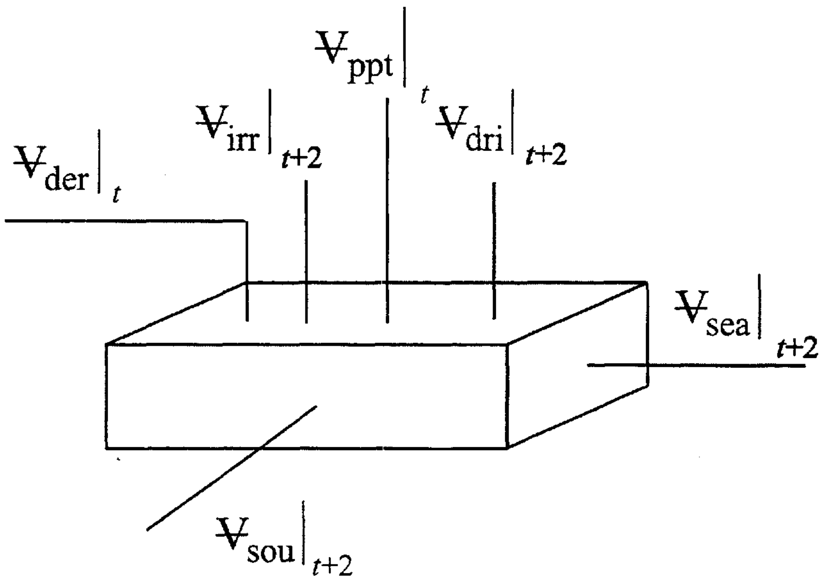

Figure 12. The diagrammatic representation of the mass balance equation with its monthly lagging components.

Results

Nearly 24×10^6 m^3 of seawater has entered and contaminated the aquifer through 12 km of shoreline over 20 years. The average porosity, according to the well tests of previous studies, is 15%, and hence if the depth of the aquifer is assumed to be 100 m very near the coast, the seawater-intrusion rate should be calculated as follows:

$$\frac{24 \times 10^6}{20 \times 0.15 \times 12 \times 10^3 \times 100} = 6.5 \text{ m/year} \qquad [2]$$

The observed intrusion velocity of NaCl concentration seems to be higher than the calculated value, as it even reaches 150 m/year at some locations. The amount of water that the people in the south pump annually from the aquifer is 8.5×10^6 m^3, which is about 16% of the annual water replenishment (safe yield) of the aquifer.

The total remaining available saturated volume of the aquifer, as of September 1997, is an estimated 1000×10^6 m^3. The yearly amount of water pumped in excess of the safe yield capacity was nearly 20×10^6 m^3; hence, at this rate, the water-pumping will deplete the aquifer in less than 50 years.

Recommendations and conclusions

Actually, the primary objective of basin management is to obtain the maximum quantity of water to meet qualitative requirements at the least cost (Todd 1980). This study should raise overall awareness of the problems and help to instigate more effective programs to tackle them. A new approach of local or regional water-resources management may minimize the effects of increasing salinity where this would benefit the region in both economic and environmental terms.

Through correct and adequate management of this coastal aquifer the region can and must maintain a balanced water budget, to maximize long-term, as well as immediate, benefits (ASCE 1996a, b). Hence, another recommendation of this study is to develop a master plan, with the consensus of the people on both sides of the island, to ensure the maximum benefit from the whole of the island's water resources. Optimal management of the available water resources would require an integrated, automated system, making use of satellite data and remote-sensing techniques to evaluate hydrometeorlogical conditions. This would require constructing an Earth station to receive and process satellite signals, with an appropriate database and information management centre for the whole island. The following are some further recommendations:

- People on both sides of the island should immediately control and measure extraction of water from the wells over the study area and, to control the extraction, establish an aquifer-use law and appropriate obligations.

- Stopping the intrusion of saltwater will require raising the freshwater table above sea level. Hence, another consideration would be to examine an artificial recharge in this area to refill the over-pumped portions of the aquifer and thereby reduce the contamination.

- As a result of siltation, the existing dams in the north, constructed for recharge and irrigation, have a questionable effect on the aquifer; hence, new ones in the south should have revised priorities and locations appropriate for seepage; otherwise, evaporation losses will continue.

- The leakage losses through the pipe network are at about 40% in the north; this is an unsustainable rate of leakage and requires a proper reconditioning of the pipeline system over the whole island.

- Though initially costly, constructing several small sewage treatment plants near each city, allowing use of treated water for irrigation of nearby lands, would be beneficial in the long run. Similarly, a desalination plant or plants might be a reasonable alternative, especially for meeting drinking-water needs.

- Other options worth considering would be to bring some of the snow from the peaks of the Troodos Mountains and let the sun melt it near the foot of the mountains to obtain fresh water or even to transport water in balloons or through a pipeline from a nearby country, such as Turkey, to meet the island's municipal water requirements.

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Chapter 5

Integrated Agricultural and Water Management in the Jordan Valley

Tareq G. Al-Zabet

Introduction

The Jordan Valley is a low-lying strip that cleaves down to the western border of the country, extending from the southern part of Tiberias Lake (the Sea of Galilee), at 212 m below sea level, to the Dead Sea at 400 m below sea level. South of the Dead Sea, the Jordan Valley turns into the hot, dry Wadi Araba. The rich valley enjoys a subtropical climate and fertile soil, allowing for year-round cultivation, especially of vegetables in winter. The area of year-round cultivation constitutes 15% of Jordan's total cultivated area. In addition, about 70% of Jordan's total production of fruits and vegetables is from its Rift Valley, which makes this valley the country's food bowl.

Agricultural development in the Jordan Valley started in the mid-1950s. Since then the public sector has invested more than 1.2 billion United States dollars in developing the valley, with cooperation from the private sector. The huge investment has turned the Jordan Valley into a distinguished national achievement, a more than 5-fold increase in the agricultural land and a 30-fold increase in production.

The Jordan Valley comprises four distinct agricultural zones, based on the altitude, climate, soil type, and water resources (Table 1).

Class-A soil is deep and level and has good permeability, low salinity, and no clay (Marl). This type of soil is suitable for all types of crop. Class-B soil is similar to Class A but is shallower, less permeable, and slightly more saline. Class-C and class-D soils are shallow and have high salinity and low permeability, as a result of the impediment offered by its clay layers (Abu-Sharar 1995).

The agricultural pattern in the 1950s was as follows: 75% of the agricultural land for field crops, 19% for vegetables, and 6% for fruit trees. This pattern took into consideration the limited water resources and their seasonal fluctuation. Parallel to the development projects in the valley between 1953 and 1986, the government proposed various agricultural patterns without the farmers' cooperation. Consequently, the farmers grew crops with the highest commercial value,

Table 1. Main features of agricultural zones in the Jordan Valley, 1998.

Characteristics	Zone 1	Zone 2	Zone 3	Zone 4
Elevation below sea level (m)	205–235	235–315	315–395	395–430
Administrative centre	North Shouna	Deir Ala'a	South Shouna	Safi
Total degree of aridity	Semi-arid	Semi-arid–arid	Arid–severely arid	Severely arid
Class-A soil area (%)	43	29	18	12
Class-B soil area (%)	41	27	17	13
Class-C soil area (%)	13	12	7	50
Class-D soil area (%)	3	32	58	25

Source: JVA (1998).

regardless of their impact on water resources or the soil. The noncooperation of the farmers in the various zones has created problems of water shortage, marketing, and soil depletion. Currently, the fruit trees range from 55% in zone 1 to 34% in zone 3 (Figure 1).

This study examined the use of integrated agricultural and water management, using the telescopic-refinement approach, to optimize land use with maximum water-value return. Using this approach one divides the Jordan Valley into two scales, the local and regional. The local scale comprises each zone with agricultural practices for analysis and major problems. This approach identifies solutions on the local scale to enhance productivity and minimize water consumption. On the regional scale, which comprises the whole Jordan Valley, an integrated approach tackles the problems common to all four zones to make the agricultural sector of the valley more efficient. The core of this scheme is to establish sound agricultural practices in each zone, with a view to integrating the various agricultural zones.

Description of Jordan Valley sectoral zones

Zone 1 (North Shouna)

Zone 1 has a semi-arid climate. Class-A and class-B soils constitute about 84% of the total area. Production in zone 1 constitutes about 44% of the total for the whole valley (Table 2).

The semi-arid climate, fertile soil, and the abundance of good water quality of the King Abdullah Canal enable this zone to support any agricultural crop. Nevertheless, for the following reasons, farmers tend to enlarge the area devoted to fruit trees at the expense of vegetables and field crops: (1) fruit prices are always higher and more stable than those of vegetables; (2) the risk of changing agricultural policies, especially in drought seasons, is less with fruit trees; and (3) growing fruit trees always occupies a higher social rank in the minds of farmers, who see it as a sign of wealth and power.

The expansion of fruit trees (55% in 1998) has exhausted most of the water supply available in summer, causing water shortages in zones 2 and 3. In zone 1, 49% of the farmers are owners–managers running and financing their own farms (Table 3). This type of management is considered the most efficient type, where the owners use advanced technologies to increase production efficiency, and tend to be better able to obtain loans and government grants.

Advancements in farming fruit trees include new types more tolerant and resistant to insects and diseases. Also, farmers are implementing new fundamental

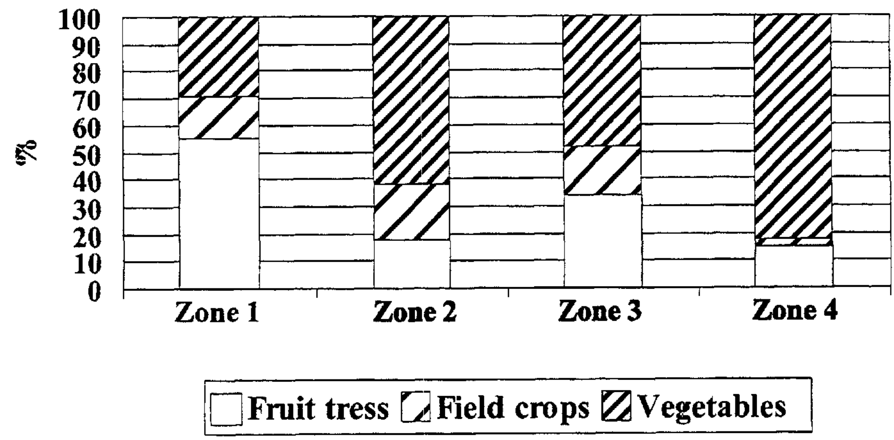

Figure 1. Farm-crop percentages in each area, 1998. Source: Harza JRV Group (1996).

fertilization methods. The major drawback is the farmers' typical use of open canals for irrigation and very limited use of drip irrigation and other water-saving devices (5–10%). Wheat, tomato, and potato constitute the major vegetable and field crops.

In crops other than fruit trees, irrigation methods have improved dramatically. About 80–90% of the vegetables and field crops are irrigated using drip irrigation and mulch. Zone 1 had few greenhouses at the time of the study, as they are inefficient at protecting the vegetables from the winter cold. Drip-irrigation efficiency failed to exceed 60–70%. Major problems have been mainly the expansion of the fruit-tree area at the expense of vegetables and field crops, the use of open-canal methods to irrigate the fruit trees, and farming of crops with low economic return.

Zone 2 (Deir Ala'a)

Class-A and class-B soils in zone 2 constitute only 50% of the total area but make the soil more suitable for growing vegetables. Vegetables and field crops are grown on 78% of agricultural land, which is a very good percentage and meets the goals of the initial development plans for this zone. Nevertheless, agricultural land makes up about 78% of the area of zone 2. This is due mainly to shortages of water and lower water quality, as a result of the partial use of low-quality treated wastewater. Another problem lies in the agricultural pattern. Typical vegetable

Table 2. Crop distribution and percentage of land suitable for agriculture in each zone.

Characteristics	Zone 1	Zone 2	Zone 3	Zone 4
Land suitable for agriculture (donum)	132 000	123 300	142 600	83 700
Actual agricultural area (donum)	128 838.2	89 303.6	33 734	41 503.8
Present agricultural area (%)	98	72	48	50
Fruit trees (%)	55	18	34	15
Field crops (%)	16	20	18	3
Vegetables (%)	29	62	48	82

Source: MOA (1998).
Note: 1 donum = 0.1 ha.

Table 3. Owner and management type in the Jordan Valley.

	Zone 1	Zone 2	Zone 3	Zone 4
Agricultural units managed directly by owners (%)	49	39	46	43
Agricultural units managed by others (%)	51	61	54	57

Source: GSD (1990–98).

crops, mainly tomato, constitute the highest percentage of farmed vegetables. The low economic return for tomatoes, plus the marketing problems each year from excess tomatoes are clear indications of the contrast between farmers' typical agricultural practices and the changing market demand for their crops.

Zone 3 (South Shouna)

Class-C and class-D soils make up about 65% of the total agricultural area. Water shortages and low-quality water from King Talal Dam, supplies 60–80% of total water, add to the problem and decrease crops productivity.

Another noticeable aspect is the increase in fruit trees, especially banana trees, at the expense of vegetables. In contrast to Zone 1, which has fairly abundant water of good quality and fertile soil, making fruit farming feasible, zone 3 has no such conditions, and irrigating fruit trees there depends mainly on private wells with highly saline groundwater. Major problems with vegetables stem from typical farming practices, excess production, and marketing difficulties.

Zone 4 (Safi)

Class-C and class-D soils constitute 75% of total area. Al-Hasa, Al-karak, and Ibn Hamad side wades are the main sources of water. The good water quality (total dissolved solids: 400–650 mg/L) minimizes the effects of the low-quality soil, but shallow soil cover still limits fruit farming. Vegetables and field crops are grown on 85% of agricultural land. Farmers increase or decrease the size of the vegetable-crop areas each season, based on the available water supply, and therefore have more flexibility than the fruit-tree growers, who cannot minimize the irrigated-tree areas when there is water-shortage problem. The main problems are similar to those in zone 3.

Local-scale management

Zone 1

The fertile soil and abundance of water in zone 1 make it too difficult to control the expansion of fruit trees. The region should take two major actions. First, it should make water prices reflect its real cost. This will force the farmers to stop the expansion of farming fruits and force them to look for other crops with higher economic value. Second, the region should improve irrigation techniques and make them suitable for both trees and vegetables. With efficient use of drip irrigation, water consumption would fall by more than 50%. The region could make other uses of this water.

Zone 2

Zone 2 seems a real vegetable basket. However, it has a real need to improve the efficiency of drip irrigation. The farmers need training courses and educational programs on economic agricultural crops and ways to promote them, using a more dynamic demand-information feedback system.

Zone 3

Zone 3 should have restrictions on fruit farming, especially farming of bananas. This crop has low export demand because of its quality and storage problems and consumes too much water. Fruit trees in this area are generally not economically feasible and put pressure on the already limited water resources and exhausted soil. Farmers in zone 3 should use new techniques to improve the efficiency of the drip irrigation for vegetables, as in zone 2. They should shift to new types of crops with higher economic value. With this type of soil and water problems, greenhouses would be the best alternative. Using appropriate technologies in greenhouses would enhance efficiency dramatically and allow farmers to grow new types of crop, such as flowers and strawberry.

Zone 4

Zone 4 seems promising but still needs to improve its crop diversity, marketing, and irrigation system.

Regional-scale management (Jordan Valley)

Control of the agricultural pattern

Figures 2, 3, and 4 show the agricultural pattern in each zone.

Government should allow farmers to grow fruit trees only in zone 1 and keep the percentage of fruit trees at the current level. The agricultural pattern in zone 2 is optimal. The shallowness of the soil and the lower water supplies make this zone ideal for vegetables and field crops. The vegetables and field crops constitute about 78% of total area. Zone 2 should maintain its current agricultural pattern and level of production. The agricultural pattern in zone 3 suffers from major problems and a real need to take corrective measures. Fruit trees, mostly banana, are grown on 34% of total agricultural land, which is an inadequate percentage that this zone should reduce. Farmers in this area should use greenhouses and put special emphasis on crops with high economic return. Growers should use zone 4 for vegetables and field crops.

Management of crop types

Among fruit trees, citrus and banana are the major crops. Although the farmers were introducing new types, such as avocado, mangoes, and palm trees, these crops did not succeed in all zones. The region needs more studies to find fruit trees with economic value, capable of growing in the Jordan Valley. Among vegetables, the main crops are tomatoes, cucumbers, and eggplants. Farmers in Jordan have a real need to shift to more economic crops, such as strawberry, which have low water requirements, a big market, and good economical returns (Al-Qasem 1995).

Improving irrigation

Farmers in Jordan need to adapt irrigation techniques, especially to fruit trees. Currently, growers irrigate more than 90% of the fruit trees, using open canals. Drip irrigation has been unsuccessful. The region needs more studies to adopt or

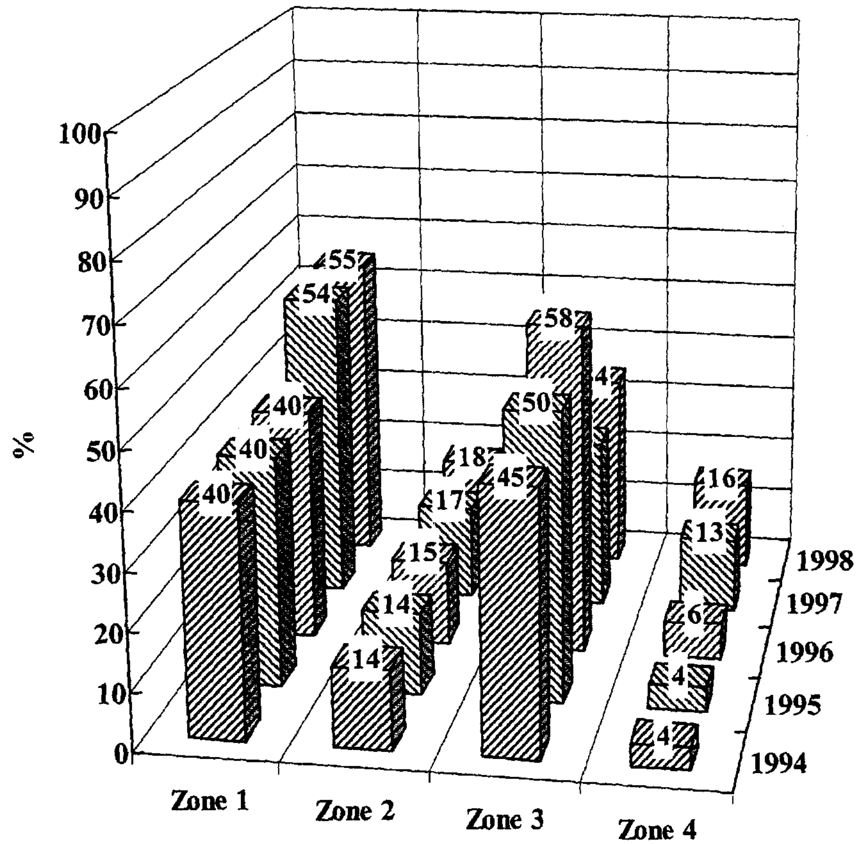

Figure 2. Fruit-tree distribution in the Jordan Valley, 1994–98. Source: MOA (1998).

invent new drip-irrigation systems suitable for its soil. Farmers are using new methods, such as special sprinklers and potentiometers, but still on a small scale, as a result of their high costs. The study found the greenhouse efficiency for vegetables was low, as 42% in winter; and 61%, in summer. This was due to technical problems, such as humidity and soil moisture, which farmers can easily handle by modifying the ventilation systems.

Integrated pesticide management

In 1994, the cost of chemical pesticides reached about 24% of operating costs. Farmers' not knowing how to use chemical pesticides causes major damage to soil, crops, and groundwater. The current trend is to shift to integrated pesticide

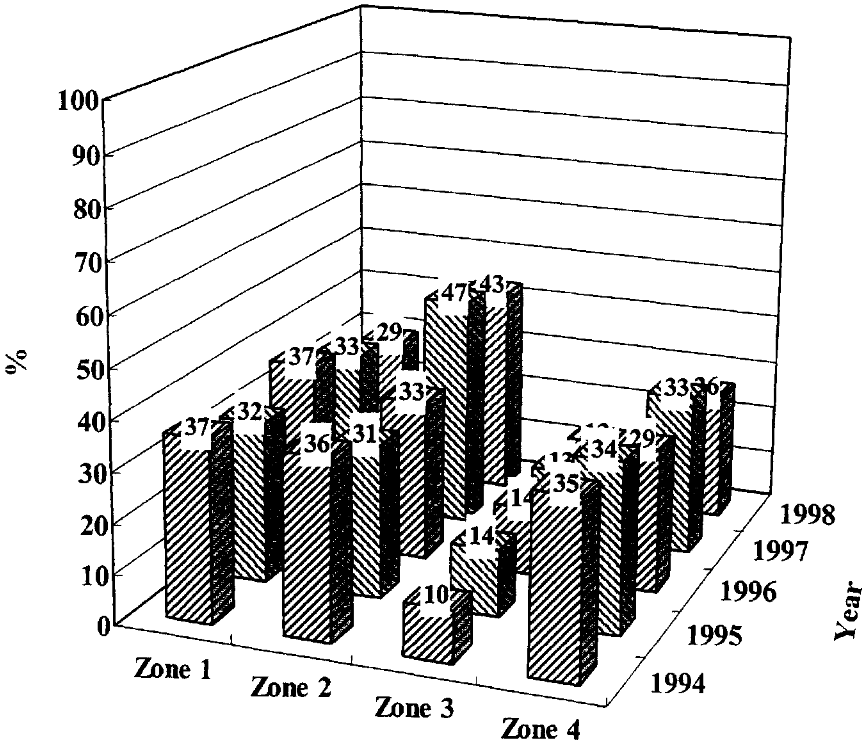

Figure 3. Vegetable-crop distribution in the Jordan Valley, 1994–98. Source: MOA (1998).

management, with the help of the Agricultural Research and Technology Transfer Centre. However, this program is expanding and is expected to increase its role in the Jordan Valley.

Pricing

The cost of water has risen from 6 to 15 Jordanian dinars (JOD) / 1000 m^3 (in 2002, 0.71660 JOD = 1 United States dollar [USD]). The new tariff is proportional to consumption. The more water consumed, the higher the tariff. The country needs to gradually lift subsidies and allow water prices to reflect its real cost, as a step toward liberalization. The economic return from lifting subsidies would then go to developing the water-supply infrastructure and improving irrigation efficiency.

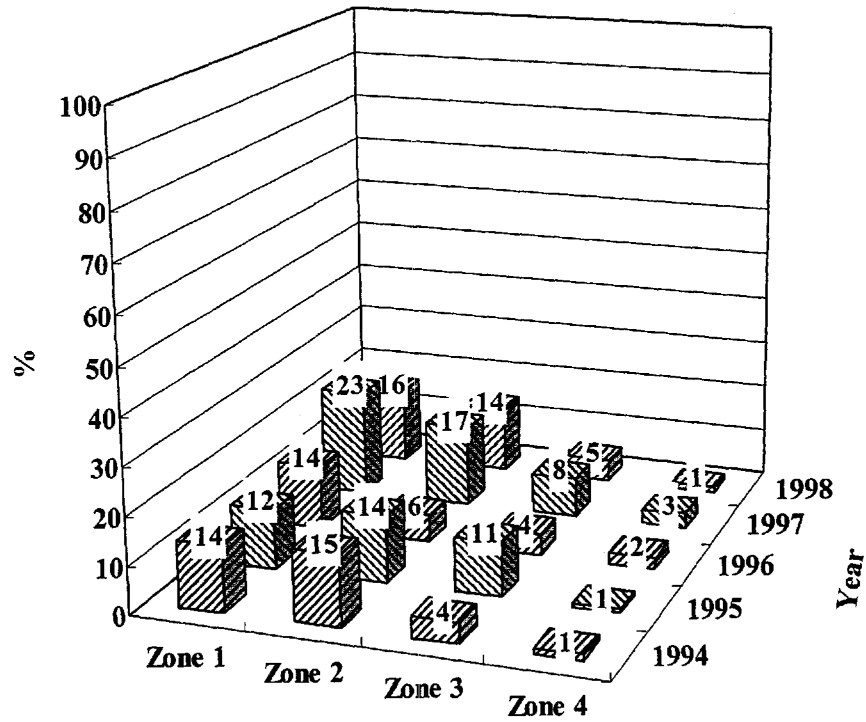

Figure 4. Field-crop distribution in the Jordan Valley, 1994–98. Source: MOA (1998).

Marketing

Marketing is the weakest point in the system. Jordan has no real forecasting system or marketing policy, and political problems also play a great role in blocking agricultural production. The farmers also refuse to trust government statements and insist on farming the typical crops, with a great risk of financial losses. Jordan needs to organize the market processes and monitor the domestic and export markets. A dynamic early feedback system for farmers on supply and demand information would be very important to make the farmers aware of what crops are in demand and help avoid overproduction.

Table 4. Water-resource allocations in the Jordan Valley.

Years	Surface water	Groundwater	Treated wastewater
1990–94 (avg) (%)	74.5	8.5	17.0

Source: Shatanawi and Jaiosi (1995).

Table 5. Percentage of water consumed by crop.

Years	Fruit trees	Vegetables	Field crops
1990–94 (avg) ($\times 10^6$ m^3)	200	110	30

Source: Shatanawi and Jaiosi (1995).

Research and development

Research and development (R&D) is very weak and inefficient. The country needs to do a lot of work on its R&D. It needs research to improve irrigation and greenhouse efficiency, pesticide control, and new, tolerant crops that consume less water and have a higher economic return. Some partial cooperation has occurred between the Agricultural Research and Technology Transfer Centre and the Jordan Valley Authority, but not to the expected level.

Water allocation

Jordan allocates around 340 $\times 10^6$ m^3/year of water to irrigation. This comes from several sources (Table 4).

The country allocates more than 30% of its water resources to irrigation in the Jordan Valley, and 80% of the water is of good quality. Using a new, modified drip-irrigation system, specially for fruit trees, farmers would save at least 30 $\times 10^6$ m^3/year (Table 5).

They would achieve more water savings if they grew crops with low water requirements.

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Chapter 6

IRRIGATION PLANNING IN LEBANON

CHALLENGES AND OPPORTUNITIES

Hüssein A. Amery

Hydrological and agricultural background

The French Mandate authority started modern irrigation planning in the early 1930s, when it helped build small earth dams, a few mountain lakes and other irrigation infrastructure. Shortly after its independence, in 1943, Lebanon paid particular attention to the agricultural sector, including irrigation, because of the country's comparative advantage in ample arable land, temperate climate, moderate to high precipitation, and strategic location, close to natural markets in the desert states of the Middle East.

Lebanon's Mediterranean climate limits precipitation to the winter season. In fact, Lebanon's precipitation occurs within 80–90 days every year. In Beirut and the Bekaa Valley, the temperatures average 7.0°C and 5.5°C in winter and 27°C and 24°C in summer (Jaber 1997). Significant spatial variation occurs in precipitation over the various parts of Lebanon, especially in the vast fertile plain of the Bekaa (Table 1).

The cultivable area is an estimated 36 000 ha, or 36% of total area. In 1992–94, the cultivated area was an estimated 189 206 ha, of which 104 120 ha was in annual crops and 85 086 ha was in permanent crops, the latter comprising mainly orchards and olive trees.

The potentially irrigable area, based on soil type and water resources, is an estimated 177 500 ha (FAO 1997), requiring 1700×10^6 m^3/year of water (Jaber 1997). A full 67 500 ha receive irrigation perennially, and 20 000 ha, seasonally. All the irrigated areas together amount to 46% of the cultivated land (FAO 1997) and consume more than 900×10^6 m^3 of water annually, or 68% of water consumption in all sectors of the economy. Calculations of agricultural water use are based on an estimated 11 200 m^3/ha a year from surface water and 8575 m^3/ha a year from groundwater (FAO 1997).

Table 1. Precipitation in the Bekaa Valley.

Geographic regions of the Bekaa Valley	Millimetres a year	Site of precipitation measuring station	Land classification
Northern Bekaa	250–275	Qa'a	Arid
Central Bekaa	500–600	Reyak	Semi-arid
Southern Bekaa	700–750	Karoun	Non-arid

Source: Adapted from Nimee (1998).

According to Shatila (1996), Lebanon has 30 aquifers, with 12 in the interior (Bekaa Valley) and 18 along the coast. Its freshwater supplies comprise 2500 $\times 10^6$ m^3 of surface water, 600 $\times 10^6$ m^3 of renewable groundwater, 1.7 $\times 10^6$ m^3 of desalinated water and 2 $\times 10^6$ m^3 of treated wastewater and drainage. Lebanon consumes 240 $\times 10^6$ m^3 of groundwater every year and uses 1225 $\times 10^6$ m^3 of water annually in all sectors of its economy and society (ESCWA 1998).

The greatest concentration of the Shia population is in the south, north, and northeast. The central government has traditionally neglected these regions, and so they are the most underdeveloped and deprived. This minority, once a marginalized sect, has organized and galvanized itself politically and become the largest religious sect, surpassing the Maronites and Sunnis. This is particularly significant because Lebanon's confessional political structure allocates political power and representation to the national sects according to the size of their population.

Some of the factors triggering the civil war were the low standard of living, government negligence of economic development in the south and northeast, and the low-intensity conflict in southern Lebanon since 1970 that had led to a massive movement of Shia refugees to Beirut. More recently, a peaceful "revolt of the hungry" in northeastern Lebanon, in 1997, deteriorated into a violent confrontation. The revolt's leader demanded the government give greater attention to economic development, including irrigation projects in the long-neglected region.

This paper surveys Lebanon's irrigation-planning strategies and argues that irrigating the south, north, and northeastern parts of the country would be critical to the national (re)integration process that the country embarked on after its protracted civil war. Also, exporting "virtual water" (that is, exports of food with all the water embedded in it) to water-stressed states in the region would have political and economic benefits for Lebanon and hydrological rewards for the importing states.

Irrigation planning

The main sources of water for irrigation are the Litani–Awali river system and subsurface waters. According to the most recent data, from 1993, 54.3% of all lands were irrigated from surface-water sources; and 45.7%, from groundwater sources (FAO 1997).

Surface irrigation is widely practiced in Lebanon. In 1993, farmers irrigated 53 500 ha, using furrow and basin methods, comprising diversion structures or simple intakes on streams or springs, open concrete main canals, and earthen or concrete secondary canals (FAO 1997). They used sprinklers to irrigate 21 000 ha, primarily potato and sugar-beet crops in the Bekaa central plain, and microirrigation techniques to irrigate 13 000 ha in the northern (Qa'a) region, central Bekaa, and the coastal plain (FAO 1997).

Rehabilitating the agricultural sector and rebuilding of the irrigation system were not high priorities of the Lebanese government during the early years following its civil war. As a result, individual farmers relied more on groundwater, and thus between 1992 and 1995, they added 2000 wells to the existing stock of more than 10 000 wells to augment the farmers' water supply (FAO 1997).

Irrigating 1 ha of land consumes an estimated 10 000–18 000 m^3 of water in Egypt, Iraq, Jordan, and Syria. That volume drops to 5000–10 000 m^3 in Lebanon, Oman, and Saudi Arabia (ESCWA 1998). The Food and Agriculture Organization of the United Nations (FAO) estimated that irrigating 1 ha of land requires 11 200 m^3/year from surface water and 8575 m^3/year from groundwater (FAO 1997). The volume of water depends on the irrigation method and the types of crop and soil. Lebanon's glaring low water-use efficiency in irrigation weakens its hydrological sustainability and constrains its food production. According to the FAO, "the average yield for irrigated wheat and barley was estimated at 5 tons/ha, as against 2.2 tons/ha for rain fed wheat and barley" (FAO 1997, p. 9). Farmers have, then, conspicuous economic incentives that will continually entice them to convert rainfed fields to irrigated farms, with all the attendant hydrological, environmental, and economic consequences.

It is useful to put these figures into relative perspective: 100 nomadic bedouins and 450 head of cattle for 3 years could use 15 000 m^3 of water needed to irrigate 1 ha. Alternatively, that volume would meet the needs of 100 urban families for 2 years or 100 hotel guests for 55 days (ESCWA 1998).

The country's drive to achieve larger and larger irrigation coverage faced the spatial "sectarian challenges" concerning which areas to irrigate and at what elevations ("levels"). An implicit question has been whether the politically and economically disadvantaged Shia have as much access to irrigation as the more advantaged Maronites and Sunnis? This challenge — as well as other factors, such as difficulties in financing some of the projects, corruption, and political instability — greatly slow the country's progress in meeting its agricultural objectives.

Lebanon established the National Authority for the Litani River (NALR), effective 14 August 1954. Its objectives were to implement the Litani project, drain and irrigate lands, and provide potable water and electricity within a comprehensive water-planning strategy for Lebanon. In 1955, the government applied for, and received, a $24 million loan from the World Bank to initiate work of this project (Sayigh 1978) (US dollars throughout). This included construction of hydroelectric-power plants in Markaba and Awali (96 MW), Jun (48 MW), and Awali (36 MW) and the irrigation of 15 000 ha (Sharaf ad-Din 1994).

The project Irrigating the South was first studied in 1964 and had its economic-feasibility study completed in 1965. However, delays resulted from disagreement over the elevation to irrigate and, later, the instability prevailing after the Israeli bombardment and occupation in southern Lebanon.

In 1964, NALR conducted a study to reclaim and irrigate 5000 ha between Qab Illyas and Jib Janeen. The project straightened and deepened the channel of the Litani River north of Karoun between 1965 and 1970. In the mid- to late 1990s, some environmental organizations started to demand protection for the natural wetlands near Qab Illyas and Bir Illyas, because of their biodiversity, aquatic life, and role in regulating hydrological dynamics (Srour and Sleiman 1998).

On the 29th August 1973, the Council of Ministers agreed to implement the first phase of Jabal A'mil irrigation project, by building the infrastructure needed to provide water to areas located up to 800 m asl. In 1974, the parliament voted to allocate 191 million Lebanese lira to implement the project (Assafir 1994) (conversion estimated at 61 million United States dollars). These decisions put an end to what had been dubbed, then, the "war over elevations."

In 1994, 4 years after the civil war, Lebanon secured from the World Bank a low-interest (8%) $57-million loan to help rehabilitate and expand Lebanon's existing irrigation projects (Iktissadiat 1994). All in all, Lebanon has committed, had promised, or borrowed a total of $1 billion to invest in phases from the mid-1990s until around 2006. This financing will help rehabilitate much of the irrigation infrastructure and revive long-suspended projects throughout the country.

On 12 December 1992, Lebanon established the southern Litani Water Authority and Southern Water Authority, by decrees 9630 and 9628, respectively. Their mandates were to implement, oversee (regulate), and operate potable-water sources and wastewater discharge networks (Srour and Sleiman 1998).

Local farmers of the upper Litani River use some 100×10^6 m^3 of water to irrigate their fields. Another 100×10^6 m^3 comes from the lower Litani, for the same purpose. The central and western Bekaa region is the location of the Bekaa irrigation project, which will cover 121 000 ha at a cost of $300 million (Younis 1997). The following section outlines some of the major irrigation projects.

Qasmiyah–Ras al-Ein

In 1974, NALR took over the management of the small Qasimyah irrigation scheme, completed under the French Mandate, only to discover the scheme's gross economic mismanagement (Sayigh 1978).

The project irrigates the coastal areas between Zahrani and al-Mansouri on the Lebanese–Israeli border. The various Israeli invasions, as well as the Lebanese civil war, damaged much of the infrastructure, including pumping stations. When fully operational, the project will irrigate 4000 ha and have 40 km of lined canals and 6 km of tunnels and pipelines. The government will spend $7.98 million of the World Bank's loan on rehabilitating and expanding this project (Iktissadiat 1994; Younis 1997).

In addition, the Yamouneh project aims to rehabilitate the waterfall and canals, store 8×10^6 m^3 of water, and construct mountain "lakes" (holding ponds) to store 17×10^6 m^3. When the project is fully operational, the area under irrigation will reach 5000 ha. This project received $6.27 million in funding in 1994 (Assafir 1994; Iktissadiat 1994).

The Thineyaa irrigation project will cover 1700 ha at a cost of $5 million, and the A'kar–al-Barid project will cover 1600 ha at a cost of $1.86 million.

Irrigation dams

Dams are tools of economic development. They allow countries to use their "natural capital" for economic development, by generating more hydroelectricity and increasing the agricultural yields (of lucrative crops) per hectare of irrigated land. For Lebanon, building dams has an added advantage: the more the country captures and uses its surface water, the better positioned it will be to deflect calls and international pressure to share its "surplus" water, which is currently referred to as "wasted," simply because it flows into the sea. According to Srour and Sleiman (1998), an estimated 900×10^6 m^3 of surface fresh water discharges into the Mediterranean Sea every year.

This water cannot be stored because of the location of the water, steep topography, narrow river channel, and perhaps most significantly the high cost of building appropriate reservoirs. As well, the country discharges 880×10^6 m^3 of subterranean fresh water into the sea (Srour and Sleiman 1998). Most of this large volume of freshwater currently goes unused, but Lebanon could use it if it significantly expanded its irrigation schemes and initiated new ones, particularly in the water-deficient but fertile plains in the south and northeast. Irrigation is after all a huge consumer of water, and a substantial area of Lebanon's arable lands remains without irrigation.

Lebanon has always been averse to selling its water to other countries in the region. This is a politically and socially explosive issue. However, the country can get around this by capitalizing on its comparative advantage in temperate climate, moderate to high precipitation levels, arable, fertile lands (much of them currently without cultivation or without irrigation), moderately skilled agricultural labour force, and an existing moderate level of mechanization in farming. It can significantly boost its export of water-intensive crops like citrus and vegetables to lucrative markets in water-deficient states in the Middle East. With intensive farming and irrigation-driven agricultural yields, Lebanon could become the foodbasket of the Middle East. If Lebanon began to expand and modernize its agricultural sector, its neighbouring water-deficient countries would begin to import its water-intensive crops while phasing them out in their own states. Because huge amounts of water go to irrigation, redirecting even a fairly small percentage of this to the domestic and industrial sectors would immensely relieve the stress these sectors have experienced in some Middle Eastern countries. However, exporting virtual water would revitalize Lebanon's long-neglected rural periphery and significantly elevate the standard of living in most economically impoverished but agriculturally very fertile parts of the country.

Technical studies recommend that Lebanon build 16–20 dams in various parts of the country (Table 2) and identify the locations for 106 mountain ponds (Table 3) (Younis 1997).

Among existing dams, the Karoun Dam, more accurately the Albert Naqash Dam, is Lebanon's largest and essentially only dam. Its reservoir can store 220×10^6 m^3. It is located on the upper Litani River, near the town of Karoun. Engineer Salim Lahoud, the general manager in charge of building the Karoun Dam, proposed building it to withstand a military strike. The dam regulates downstream flow of the river to generate power and irrigate the upper and lower reaches of the Litani and can release water at a rate of 500 m^3/second. The Abd al-A'l hydroelectric plant, commonly known as the Markaba plant, uses 22 m^3/second of water from Lake Karoun through a 6400-m-long tunnel, which takes the water to power plants and then to the Awali River.

Table 2. Rivers on which dams are proposed in coastal area.

River names	Storage capacity ($\times 10^6$ m^3)
Khardali Nahr	70
Zhgarta Nahr	8
Al-Barid Nahr	40
A'rka Nahr	20
Al-Ustwan Nahr	15
Al-Kabeer Nahr	60
Ibrahim Nahr	35
Ad-Damour Nahr	5
Nahr Bisri	35

Source: Shatila (1996).

Table 3. Areas earmarked for mountain ponds.

Province	Caza (administratve unit)	Number of ponds
Bekaa	Ba'albeck	12
	Zahle	2
	Jib Janeen	3
	Rashaya	6
North Lebanon	Al-Batroun	1
Mount Lebanon	Beit ad-Din	1
South Lebanon	Hasbaya	1
	Jezin	1

Source: Annahar (1995).

A number of dams are proposed, primarily for irrigation and urban domestic water supply. One such dam would be on the Damour River south of Beirut, with a capacity of 175×10^6 m^3. The Damour River is 38 km long and originates from Dahr al-Bayder at an elevation of 1510 m asl. The river's average water discharge is 306×10^6 m^3/year, and the area of its watershed is 288 km^2. The reservoir behind a dam on the Damour River would (1) supply metropolitan Beirut; (2) irrigate the Damour and other nearby coastal plains; and (3) provide the water needed for the industrial and recreational–tourist industries south of Beirut (Annahar 1997).

The Bisri Dam on the Awali River is in its final design stage. Its storage capacity will be 128×10^6 m^3, and it is intended primarily to supply water to metropolitan Beirut.

The Khardale Dam on the lower–middle reach of the Litani River has a storage capacity of 128×10^6 m^3. Work on the Khardali Dam was suspended in the 1960s, because of the war of the irrigation levels, the civil war, and the dam's precarious location on the edge of the Israeli-occupied strip in southern Lebanon, which the Israeli army was evacuating in June–July 2000, having kept it under military control for 22 years.

Since the early 1960s Lebanon has been helping farmers construct dirt reservoirs, primarily in the mountains, to collect rain and flood water during winter. The stored water would then be of use to farmers for irrigation and watering animals during the dry summer, as well as to others for recreation, tourism, and household consumption.

NALR was in charge of the ponds project in the late 1970s. The capacity of each dirt reservoir ranges from 1000–10 000 m^3. Between 1965 and 1985, the ponds captured 3.605×10^6 m^3 of water throughout the state. NALR built an additional capacity of 0.394×10^6 m^3 between 1991 and 1992 (Assafir 1994). After NALR took charge of this project, it built the Kfar-Houne Lake near Dahr ad-Daraje in southern Lebanon. This is a natural lake with a storage capacity of $150\,000 \times 10^6$ m^3. It loses 110 000 m^3 of water as a result of seepage and evaporation, thus making only 40 000 m^3 available.

Al-Kawashera Lake (A'kar) is an artificial lake, with a dirt dam and an original storage capacity of 120 000 m^3 of water for irrigation and herding. This lake is under management by NALR.

Al-Mrouj Lake is near al-Ballout in the upper Matn. Cement covers the dirt dam and the lake floor. The lake can store 380 000 m^3 of potable water (Annahar 1995).

The Green Plan (Le Plan Vert) is a state institution, established in 1963, to improve farm and state lands and develop water reservoirs for agriculture. Specifically, its mandate is to help landowners, especially those with small plots and meagre means, clear their properties of stones, build terracing, obtain cheap tractor services, intensify tree-planting from nurseries run by the Green Plan, and dig wells, or otherwise obtain and use water for irrigation. During the period of 1964–92, the Green Plan developed hundreds of earthen and concrete water-storage ponds, the former containing 3.5×10^6 m^3; and the latter, 0.35×10^6 m^3. The maximum per-unit capacity of each pond is 0.2×10^6 m^3 (FAO 1997).

The technical- and economic-feasibility studies for the new dams have been ready for sometime. Lebanon's challenge now, however, is to secure funding for these projects, without which, officials argue, the country is heading for serious shortages. A rapidly creeping "new" (or long-neglected) challenge for water and irrigation development is water quality.

Water quality and irrigation

The Bekaa is Lebanon's largest province and has by far the largest area of arable land. It is also fairly arid, with near-desert precipitation near the historic city of Ba'albek. Consequently, threats to its water supplies would severely hamper the economy of the province.

Most towns and villages in the Bekaa Valley have no sewer systems, and many that have them empty their waste water completely untreated into a nearby valley and, more likely, the Litani River (Table 4). The town of Jib Janeen, around 10 km north of Lake Karoun, had a sewer system installed in the early 1990s, but its waste flows, untreated, into the adjacent Litani River. The problem becomes magnified during the summer, when the river's flow slows to a trickle, but not that of the sewer system. Furthermore, some unscrupulous farmers near Jin Janeen (and further up stream, near the city of Zahle) are known to draw water from the river to irrigate their summer crops, which they market locally and in Beirut. The impacts on people's health as a result of the farmers' use of contaminated irrigation water remain undocumented.

Over the decades, I have made countless visits to Lake Karoun and have been noticing the water is green, rather than its natural blue colour. By the end of November, at the end of the long dry season, when the lake is at its lowest point, more than 10% of its volume is waste water discharged into the upper Litani or directly into the lake from surrounding villages (Comair 1998; see also Srour and Sleiman 1998).

A "cocktail of toxic chemicals" contained in 15 800 barrels and 20 containers was exported to Lebanon, primarily from Italy, in 1987. The chemicals came from industrial processes and waste from research laboratories and consisted of heavy metals, such as Ag, CN, CN_2, Hg, $CdCN_2$, dioxin, and PCBs.

Although Lebanon eventually returned some of the barrels, more than 10 000 of them remain. People emptied some of the barrels and used them to store food or water (Annahar 1995). They emptied some into the Mediterranean Sea and others in the Kesrouan Mountains, the recharge area of a significant coastal aquifer northeast of Beirut (Hamdan 1995). Consequently, this dumping endangers groundwater and local farmers' irrigation water on their fertile coastal plain.

Table 4. Wastewater discharge into the upper Litani, May–Nov (L/second).

Region	Volume (L/second)	Location
Ba'albek	50	Litani headwaters
Zahle	300	Lower headwaters
Western Bekaa	70	Upper Litani, near Karoun
Total	420	Up to Lake Karoun

Source: Comair (1998) (see also Srour and Sleiman 1998).

The Litani watershed has 96 quarries; a mere 19 of them have government licences (Srour and Sleiman 1998). Their activities increase soil erosion and water turbidity and harm the quality of water, thus adversely affecting aquatic life and the purity of the river water.

In the Kesrouan town of Shnanir, the government has closed a massive quarry numerous times, only to have it return to normal operations a short time later. This is largely owing to the fact that the current and former officials have been part owners (Al-Azar 2000) of this lucrative enterprise. This quarry was a dump site for toxic waste from Europe, and some of it was set on fire back in 1987. The site was never decontaminated. In 2000, gravel and sand from the quarry was being used to build the Beirut–Jounieh highway, thereby spreading the contamination even farther along the coastal plain and aquifer.

Discussion and conclusions

S. Tufaili, the former secretary-general of the Hizbullah ("Party of God"), led the 1997–98 revolt of the hungry, which demanded that the central government improve the standard of living for people by initiating development projects, such as irrigation schemes in the long-neglected Hirmil-Ba'albeck region of northern Bekaa. Although the revolt was to be peaceful, it deteriorated into a violent confrontation, with people being killed or injured. This region was the heartland for the hashish and cocaine industries until the early 1990s. With American help, the government eradicated these lucrative crops but failed to supply a replacement crop or create any jobs for the displaced or impoverished workers. A mere 2 years after Tufaili launched his campaign of civil disobedience, the government initiated a project to rehabilitate and expand Lake Kawashra, built in the 1970s, so that now it stores up to 350 000 m^3 of water. This will allow the government to pipe water to 13 villages in Jabal Akroum in the A'kar region (Abullah 1999).

With the liberation of south Lebanon, after 22 years of occupation, the area urgently needs a "Marshal Plan" to uplift its residents' quality of life to national levels. Irrigation projects would very likely be high on the agenda of government officials, as a key step to enticing people to remain in the region or return to it. Would governmental neglect of the south lead to civil tensions in war-weary Lebanon?

The country could more efficiently manage its water resources in the short term, which would "create" water for other more needy parts of the country. In 1998, NALR provided some western Bekaa farmers with equipment to efficiently irrigate 900 ha. This helped to drop water use per ha from 15 000 m^3/year, as in the Qasimyah–Ras al-Ain project, to 6500 m^3/year (Wimmen 1999). In the Qasimyah–Ras al-Ain project, most farmers rely on furrow irrigation.

The drip, or microirrigation, technique appeared in the 1960s, and now farmers use it primarily in water-stressed countries like Australia, Israel, Jordan, New Zealand, and some regions of the United States. Drip irrigation delivers water to individual plants via plastic tubes. Thus it uses 30–50% less water than surface irrigation (Tuijil 1993). Although drip irrigation is efficient, it is energy and capital intensive and requires fairly clean water so that its fine delivery tubes do not clog up.

Planting trees to shelter crops reduces evaporation and transpiration from the planted ecosystem by 13–20% during the growing season. This increases crop yields for corn by 10–74% (Gregersen et al. 1989). Sheltering crops also reduces wind soil erosion. Controlling erosion helps conserve water by reducing rapid runoff. As Pimentel et al. (1997, p. 104) remarked, "protecting forests and other biological resources facilitates effective use of water resources and helps maintain the hydrological cycle."

Lebanon should take immediate steps to conserve water. This would provide more water and more time to pursue funding for some of its urgently needed water-development schemes for, among other things, extensive irrigation and urban water supply. The human and physical–natural resources make agricultural development through irrigation a sensible approach to improving the quality of life for people in the long-neglected northeastern and southern regions. This would cement their identity and loyalty to the central government and, in turn, enhance national unity and civil harmony and stability.

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Chapter 7

Improvement of Irrigation Unions in the GAP Region

Erkan Alemdaroğlu

Introduction

Projection area of Turkey is 77.945 2 × 10^6 ha. Turkey has 206.6 × 10^9 m^3 of the potential water reserves. Annual water-use potential of Turkey is 106.6 × 10^9 m^3, and 95.1 × 10^9 m^3 of this is underground water. However, annual use of this potential is only 31 × 10^9 m^3. The water potential of the Euphrates and Tigris basins is 53 × 10^9 m^3, and 32 × 10^9 m^3 of this potential belongs to the Euphrates basin; the remaining 21 × 10^9 m^3, to the Tigris. These basins hold 30% of Turkey's potential. Total agricultural land of Turkey is 28 × 10^6 ha, but only 8.5 × 10^6 ha of this is economically irrigable.

Turkey currently has some 4.4 × 10^6 ha under irrigation, and State Hydraulic Works (SHW) has planned, designed, and implemented schemes on about 1.7 × 10^6 ha. The General Directorate of Rural Services (GDRS) has initiated smaller scale schemes on about 1.0 × 10^6 ha, and local public and private schemes occupy the remaining irrigated areas.

The Güneydoğu Anadolu Projesi (GAP, Southeastern Anatolia Development Project) is a multisectorial development plan for one of the less developed parts of Turkey, embracing the sectors of agriculture, industry, transportation, health, and education. Within the agricultural sector, planners at SHW have initiated a long-term program to implement 13 major irrigation projects, with 7 in the lower Euphrates subbasin and 6 in the Tigris subbasin, covering a further 1.7 × 10^6 ha, or about one-quarter of all Turkey's irrigable land. This will increase the irrigated area from 3% to 53% of the available irrigable land within the GAP region. The total irrigation area subdivides into 26 subareas, with hydraulically independent irrigation systems.

SHW developed most schemes and currently manages their operation and maintenance (O&M), typically retaining responsibility for supply systems from headwork source down to, and including, the tertiary-level systems (there are main, secondary, and tertiary canals). Current fees for users are low and insufficient to meet the cost of maintaining a satisfactory standard of O&M.

The continued growth in irrigated area increases the burden on SHW's budget and adds to the complexity of its management role. Since 1970 SHW has promoted "irrigation groups" of water users, responsible for liaison between individual farmers and SHW for ordering and distributing water and performing minor maintenance of the tertiary systems. As is very well known, in all management styles participation is essential for sustainability, effectiveness, and productivity. Users' participation in the decision-making process ensures that they feel responsible for the decisions they make.

Without doubt, the preservation of natural resources, such as water and soil, is essential to securing the next generations' food supply. Sustainability of natural resources depends on user participation and human-resource development.

Irrigation and irrigation management

Irrigation is the science of supplying water to meet crop-production needs, either by itself or together with rainfall. It involves a social environment, including farmers, irrigation-O&M personnel, managers of systems, irrigation agencies or departments, farmers' organizations, irrigators' associations, and numerous other individuals and institutions. It involves an economic environment, in which inputs have costs and outputs have values, investments require payment of principal and interest, and farmers grow commodities for domestic urban populations or export, together with resources imported to support national production. It involves a biological environment, in which the major output results from a process of biological growth and numerous life cycles and growth habits determine the quality and quantity of the product. It involves a physical environment, including the soil, the water, the atmospheric processes, and the numerous methods farmers use to control the water. Finally, it requires the social, economic, biological, and physical principles to supply water to grow a crop.

The irrigation system is the entire set of interacting social, economic, biological, physical factors, objects, and entities, from the source of water, through to the conveyance system to the farm and the land, including the drainage network to remove excess water from the boundary of the irrigation service area. This includes the irrigation agency, its personnel, the farmers, their organizations, and all of the related institutions serving irrigation.

Management is the act of controlling, conducting, or supervising a process, with feedback to improve its performance and rules and procedures to guide the control of the process. Management is a practice at many levels of the production system: decision-making for water allocation among various and often competing users, control of water sources, diversion and conveyance of water, distribution of water to farmers, and their conveyance, allocating, and use of it, and the removal of surplus when necessary.

Irrigation water management, then, is the application of all the contributing disciplines — primarily sociology, agronomy, and engineering — to the process of supplying, diverting, storing, allocating, conveying, distributing, applying, and draining of water to produce a crop.

Irrigation system management is that portion of irrigation water management that integrates supervision and control of water sources through the steps of the irrigation process, including those taken by farmers or groups of farmers in their cropping enterprises, as well as the farm drainage network. Irrigation system management subdivides further into categories of main-, secondary-, and tertiary-system management. The process of irrigation system management in its most general form must include irrigation water requirements, from the root zone of the crop, to the field, and to the farm (or the farm subsystem), to allocate and supply a sufficient quantity of water, with an adequate quality, and on time to conveniently meet the needs of the crop.

Irrigation system management deals with abstracting water from the source, its allocation, conveyance, distribution, and the removal of excess water. Usually, it is the responsibility of a central irrigation bureaucracy, which generally looks after the system, giving instructions and applying rewards and sanctions. Sometimes it is the responsibility of a joint irrigation agency and farmer organization, where through irrigators' (water users') associations farmers collectively assume responsibility and authority over much of the conveyance and distribution system, perhaps at the tertiary- or secondary-system level, or both.

The irrigation water management at the farm level is the responsibility of the farmer, whereas the government has responsibility for the water source and secondary or tertiary systems.

Farm water management deals with the water in the hands of the individual farmer or a small community of irrigators who share an irrigation turnout and must, in turn, agree on a mutually beneficial allocation, conveyance, and application of water to crops. Most of the organization occurring at this level is informal and accomplished without written rules or an organizational charter. All participants generally understand well the norms for use of water and the sanctions for excessive use. They make informal arrangements for periodic individual or group maintenance work, for water-sharing in times of water scarcity, and for conflict management. Farm water management is a subset of overall farm management and focuses primarily on storing water in the crop root zone, with a view to making the cropping exercise productive and efficient. The outcome of the cropping enterprise largely depends on how well farmers accomplish this placement of water in the plant root zone.

Sustainable irrigation

The sustainability of irrigation has internal prerequisites, such as quality of design, construction according to design, proper system O&M, effective monitoring and evaluation, and a commitment to making alterations to improve system maintenance when needed. Some of the external factors involved in irrigation sustainability are the quality of the upper drainage basins and the effects of policies and practices for agriculture, the environment, and spatial development.

Some reasons for the failure of irrigation sustainability are insufficient attention to quality of upper drainage basins, water logging and salinity, and waste of water through inappropriate methods or technologies and excessive watering. Other reasons are the lack of incentives for water conservation, lack of legislative or institutional arrangements, difficulties with enforcement, and inadequate training of users.

Although these seem to be the barriers to sustainability, the core factor is the human aspect of irrigation. As the users are at the centre of the irrigation process, human-resource development in irrigation should have particular emphasis, which means users should have training in sustainable-irrigation applications and support for participation.

Essential to the sustainability of the whole irrigation system is the sustainability of irrigation management. This is also essential to the sustainability of natural resources, such as water and soil. To secure the sustainability of management and thus natural resources, the users should become fully involved in the decision-making process and paying the operational costs at the grass-roots level. This can be described as the bottom-up approach.

The sustainability of any irrigation system depends very much on the organization managing it. Irrigation organizations should have the support and encouragement of surrounding related official bodies, such as ministries' local representatives, local authorities, and other official organizations or private bodies, such as companies and nongovernmental organizations. Without this support, these organizations and the irrigation system would be unable to survive in the medium and long terms.

Irrigation investment and management in Turkey and in the GAP region

SHW and GDRS invest in irrigation. SHW makes long-term, high-cost investments. GDRS makes short-term, low-cost, farm-level investments. SHW irrigation investments cover works such as dams and artificial lakes, underground water supply, irrigation canals and canalettes, main drainage canals, flood-control structures, large drinking-water systems, and electric-pump irrigation (Table 1). GDRS irrigation investments cover works such as gravity or pressurized irrigation systems with 500-L/second discharge, artificial lakes with maximum 15-m-high dam bodies, farm development services, soil studies, and mapping and research on water and soil resources.

The irrigation networks of SHW supply water to large areas, sometimes areas of more than one settlement unit. They are very complex structures. By 1993, the state managed 92.5% of all SHW irrigation. The rest had been transferred to cooperatives, irrigation districts (unions), municipalities, and village administrations (Table 2). In addition, small water-user groups have formed to operate tertiary canals. Such groups have been active since 1960 commonly in Adana and İzmir regions. The users of transferred irrigation schemes are only operating, maintaining, and managing the secondary canals and subsystems, and their cost-recovery is essential. The GAP region had 44 irrigation districts by the end of 1999; and the total irrigated land that SHW transferred to the districts was about 170×10^3 ha. The 44 in the region include the underground irrigation districts and the unions for service extension to the villages (Köye Hizmet Götürme Birlikleri). By the end of 1999, SHW had constructed and transferred irrigation schemes covering 1.536×10^6 ha. Until the end of 1995, Turkey had 184 irrigation districts, controlling an irrigation area of 893 764 ha. The first of these was the Korkuteli Irrigation District, established in 1942 (Baran 1996). By the end of 1999, the country had 304 irrigation districts, operating over an area of 1.397×10^3 ha.

GDRS irrigation schemes cover small areas, a village or a municipality, and are simpler than SHW schemes. By 1993, cooperatives operated 903 of the 15 326 facilities in Turkey, and village administrations and municipalities ran the rest. Users are responsible for the whole system, and this involves no cost-recovery.

Turkey has 8.5×10^6 ha of irrigable land; 3.8×10^6 ha of it had irrigation by 1993. SHW operated and subjected to O&M cost-recovery 208 (1 300 561 ha) of the 517 irrigation networks it opened. It transferred 176 networks (62 620 ha) to beneficiary organizations and 133 networks (115 427 ha) to people. GDRS has transferred 692 networks (244 120 ha) constructed with its cooperation to irrigation cooperatives. In the same period, GDRS transferred irrigation schemes, covering 269×10^3 ha, to 903 cooperatives and others, covering 873 650 ha, to 14 423 village administrations and municipalities. The average area of a GDRS irrigation structure is about 75 ha. This is 55 ha in the case of regulator structures, 207 ha in that of artificial lakes, and 298 ha in that of pressurized irrigation. The transfer of small-scale irrigation to village administrations or cooperatives has created few problems in O&M. A national study done in 1993 identified cooperatives as being particularly successful.

The networks opened by SHW have not had the same success. The state still manages most of those open for operation and covers their O&M costs, too. However, the budget allocation for O&M is getting smaller and smaller while the area of irrigated land is getting larger and larger (Table 3).

The decline in the irrigation ratio to 66% and the schemes' meeting only 65% of their financial requirements for O&M have been danger signals for the future irrigation.

The need for rehabilitation of irrigation structures has increased dramatically, owing to delays in maintenance, which is increasing the burden on the national budget. Nationwide activities have started to prevent similar future problems and obtain the expected performance from the networks. The GAP Regional Development Administration developed a project in 1989 to solve the problems by identifying a management, operation, and maintenance (MOM) model for the GAP region, testing it in pilot areas, and modifying it, if needed, to expand it into other parts of the GAP region. Activities of this project have included effective water use, demonstrations of modern irrigation methods, irrigated-agriculture agronomy, training and extension, and the application of the MOM model, based on a bottom-up approach.

Irrigation has two major management styles. To make the existing and proposed irrigation developments sustainable, the schemes must increase their levels of cost-recovery, bringing them into line with worldwide trends and encourage greater devolution of management responsibility to water users, so that the GAP region has no state-run irrigation schemes.

Irrigation districts

Municipality Law No. 1580, dated 30 April 1930, established the irrigation districts. Mayors and village heads within or near irrigation areas are to jointly establish the irrigation districts. Rules and regulations are very similar across irrigation

Table 1. Irrigation investment in Turkey and in the GAP region.

	Turkey		GAP	
Organization	1993 brut area (ha) [a]	1999 brut area (ha)	1993 brut area (ha)	1999 brut area (ha)
SHW	1 722 728	1 954 712	63 588	239 676
GDRS	954 850	1 133 482	46 630	56 980
SHW + GDRS	244 120	244 120	15 424	15 424
People [b]	1 000 000	1 080 000	1 60 000	118 000
Total	3 841 698	4 412 314	285 612	430 080

Source: Beyrıbey, M. 1997. Evaluation of state-run irrigation schemes. Ankara, Turkey.

Note: SHW, State Hydraulic Works; GAP, Güneydoğu Anadolu Projesi (Southeastern Anatolia Development Project); GDRS, General Directorate of Rural Services.

[a] In Turkey, a coefficient of 0.864 was used to calculate the net irrigation area.

[b] Estimated.

Table 2. Irrigation schemes transferred by SHW to organizations, 1 Dec 1999.

Organization	Number	Ratio (%)	Area (ha)	Ratio (%)	Average irrigation area (ha)
Village administration	214	30.7	32 093	2.1	150
Municipality	185	19.3	55 840	3.0	113
Irrigation district	304	43.6	1 397 001	90.9	4 594
Cooperative	42	6.0	50 582	3.3	1 204
Other	3	0.4	957	0.1	319
Total	698	100	1 536 279	100	22.1

Note: SHW, State Hydraulic Works.

districts, as they are based on typical rules and regulations. After forming an irrigation district, they submit a written application to the SHW Regional Directorate, requesting a transfer of the irrigation facilities. The administrative bodies described in the regulations — the district chair, council, and board — direct the irrigation districts.

The district council is the top administrative body of the irrigation district. It influences the selection of the chair and board members. The salaried personnel are a secretary-general, accountant, O&M technician, water-distribution people, driver, and secretary, and the chair and secretary-general supply supervision.

Irrigation cooperatives

Farmers establish irrigation cooperatives with the approval of the Ministry of Agriculture and GDRS (in accordance with the Cooperative Articles No. 1163). These cooperatives are mainly established for small-scale underground irrigation projects (schemes using underground water). Cooperatives have also taken over some state irrigation schemes to keep them operational.

A cooperative has three administrative bodies: the general assembly, an executive board, and an auditing board. The general assembly, which meets every 1–2 years, is the highest decision-making body.

Table 3. Performance indicators for SHW irrigation networks.

	Water supply								
	Net	Total	Irrigation ratio (%)	Production value (%)	Profitability	Financial efficiency (%)	Financial sufficiency (%)	Collection of water charges	Sustainably irrigated land (%)
Turkey	2.00	1.04	66	65	4.0	64	65	36	97
GAP	1.63	0.89	78	76	4.7	80	75	14	98

Source: SHW (various publications).
Note: SHW, State Hydraulic Works; GAP, Güneydoğu Anadolu Projesi (Southeastern Anatolia Development Project).

Problems to be addressed in irrigation management

Problems in irrigation management are institutional and technical.

The main problem with the institutional structure is the inadequate participation of water users. The majority of the farmers are unaware of their responsibilities and rights in the irrigation districts, the organization that distributes water, the department collecting irrigation charges, and the ways it uses the money. Some farmers think SHW supplies irrigation water and has responsibility for O&M of the facilities. This shows that water users are still unaware of their responsibilities in management and ill-prepared to take them on.

Although farmers should start training at least 1 year before SHW transfers the system into their hands, neglect of this task has meant that water users at every level of the organization have inadequate training. SHW, the provincial agricultural directorate, and the Regional Department of Agrarian Reform do prepare and deliver some training services. However, such training should be more adequate and systematic, so as to help establish the institutional bodies of the irrigation district. Owing to the failure to give the newly formed irrigation districts the needed training for people to use water and operate the irrigation facilities, they are unable to operate them at a desired level and do maintenance and repair work. They are unable to fully ensure hierarchical order, and they occassionally encounter problems owing to their failure to understand the duties and responsibilities.

The rules and regulations in the irrigation districts have many deficiencies. The regulations describe the duties and responsibilities of the council and board chair in detail, but fail to mention those of the secretary-general, personnel in charge, and irrigators. No written documents describe how to split up the service shares for facilities providing services for more than one unit, such as dams, regulators, tunnels, siphons, and check structures (structures to distribute water to canalettes) described as joint facilities, or how to make repayments. It is expected that parliament's ratification of this law (Municipal Law No. 1580) will tackle many similar problems.

Irrigation districts must have financial, administrative, and technical inspections. Ideally, farmers using the water would conduct such inspections (expenses announced on the noticeboard of the district water-users association), and a district's own inspectors would conduct an internal inspection. But no law or regulation is in place to allow irrigators to inspect the irrigation district.

Significant problems are encountered in the collection of water charges, and personnel have problems with job security, and this adversely affects their confidence in the organization.

Management, operation, and maintenance model for GAP irrigation systems

The need for an MOM model

Irrigated agriculture is the foundation of sustained development in the GAP region. If it fails to perform up to expectation, this would seriously weaken the economic base of the region and threaten the sustainability of the rapid development now taking place.

The country has already invested in infrastructure for some 4×10^6 ha as a whole and is currently engaged in another massive drive to bring a further 1.7×10^6 ha under irrigation in southeastern Anatolia. The additional demands of newly developed areas will become an excessive burden. Farmers will inevitably have to spread limited resources over a wider area, with the consequent fall in the standard of system MOM, and quality of technical support for farmers. This in turn will result in falling levels of service, reduced water-use efficiency (WUE), increased salinity and drainage problems, and lower crop production. As farmers lose their ability to pay for services, the quality of service will fall, thus creating a downward spiral. The region must make fundamental changes in its institutional structure to ensure the full and efficient use of farmers' management and the resources as a whole to maximize WUE and crop production.

As long as the region has as many institutional and technical problems as it does, this will endanger the sustainability of irrigation systems and resources. The MOM model should overcome those problems.

In addition, many existing schemes suffer from high water losses in the distribution systems, much of it attributable to insufficient resources for maintenance. In many cases, irrigation use at the farm level is not as efficient as it could be, because of insufficient investment in land preparation at the implementation stage and only very limited technical advice for the farmers on efficient irrigation methods.

Most of these difficulties arise from the current institutional framework, and only a basic reform of the structure could resolve these issues.

The scope of the overall MOM model

The overall MOM model has the following aspects:

- Institutional arrangements that define the major organizational entities, their forms (for example, government department, authority, cooperative) and their functions, responsibilities, and interdependencies;

- Organizational arrangements that define the lines of communication, co-ordination, accountability, and responsibility of these entities;

- Management arrangements that define the organizational structures of the key entities, their systems and procedures, and their resources and skills;

- Guidelines for planning, designing, operating, and maintaining the physical infrastructure;

- Guidelines for good on-farm practices;

- Guidelines for human-resource development (for example, training and materials);

- System for performance monitoring and evaluation, with arrangements for giving feedback from the evaluation in the form of modified guidelines and management arrangements; and

- Description of the enabling legislation to implement the institutional and management arrangements and enforce the guidelines.

The MOM management model

The MOM management model describes how best to organize the O&M of irrigated-agricultural systems for conditions of GAP. This continuous process is distinct from the time-bound events, such as planning and design of irrigation and drainage systems, which, though very important to efficient operations, have a finite lifespan and have no need to be sustained beyond the implementation stage. As such, the MOM management model is a continuous management process and the core activity that the region must properly establish and sustain efficiently to fully realize the objectives of the GAP MOM study.

Selecting the most appropriate and effective institutional form for each of the core components is critical, and it has therefore been the focus of the model-selection process.

The major objectives of the MOM model

The major objectives of the MOM model are the following:

- To maximize net benefits of irrigated agriculture in the GAP region; and
- To ensure the financial and physical sustainability of irrigated agriculture in the region.

Moreover it must be quick to implement and have the flexibility to respond to changing needs and requirements over time.

Fundamental requirements

The model has to satisfy a number of fundamental requirements:

- *Optimal returns from use of land and water* — In this region, water is the scarcer resource and to maximize benefits the region would need to optimize the returns per unit of water. The land is effectively a nonrenewable resource of great value, whose productive capability must be carefully safeguarded for future generations.
- *Overall financial sustainability* — Irrigation relies on a well-maintained and well-operated infrastructure. Unless irrigated agriculture produces a sufficient financial surplus to allow for adequate O&M, the system's efficiency will deteriorate, productivity will fall, and a downward spiral of degeneration will result. The surplus should also be sufficient to permit investment in research and improvements in farming practices to maintain and improve productivity and the quality of life for people in the area.
- *Protection of national interests and resources* — To sustain its development, the region must preserve its national resources, both in terms of quantity and quality, while pursuing national interests. The model must include mechanisms to assess and monitor such impacts and measures to plan for and mitigate negative trends.
- *Social harmony* — The model can only achieve maximum production and assured sustainability in an environment of social harmony.

- *Equitable allocation of water* — At all times and particularly when water is scarce, equitable allocation of water is needed for social harmony, WUE, and maximum financial and physical sustainability.

- *Human-resource development* — Optimal mobilization of the skills, experience, enterprise, and labour of the human resources in the region must be an objective of the management system to maximize net returns. Human resources are as essential as water and land to production, and to make best use of all available resources is a goal of good management.

- *Skills development* — The capacity to develop skills would be essential to meeting the growing demands of the region as it develops. People in the region need to learn and develop capability through practical experience, and the model must make specific provisions for institutions, specially trained persons, and teaching aids for this purpose and recognize and implement such training as a continuous process, rather than a solitary event linked to initial implementation.

- *Flexibility* — So that the management systems can respond to change, it must recognize that development is a dynamic process, be flexible enough to respond to the changing needs and requirements, and be ready to absorb and benefit from improved technologies and knowledge.

Above all else, the model must take into account the actual conditions of the region, that is, its institutional, legal, cultural, and physical characteristics and constraints.

Finally, for the management system to be organizationally functional and efficient in meeting targets, it must have certain physical attributes and exhibit some well-known but elusive characteristics described below.

GAP MOM approach — participation

The comments and opinions of the people who will use the irrigation facilities constructed in Turkey are not generally incorporated into the stages of planning, design, and O&M of such facilities. On completion of the soil and water surveys, public establishments prepare planning reports and projects, then generally engage construction firms for construction, but deem it unnecessary to have the farmers' active participation in the formation of management for the irrigation districts, implementation, or O&M.

The GAP MOM project hopes to make the most efficient use of soil and water resources for irrigated farming in the GAP region. It can achieve this if it lets users have the power to control the resources. Physical structures are complex and require extensive engineering services. All steps taken to operate such complex structures must follow technical, economic, and social criteria, as well as ensuring continuous development. The GAP MOM project will endeavour to expand on farm implementation methods compatible with irrigated farming, as well as ensuring the efficient participation of the farmers in the MOM of the irrigation facilities. It will persuade farmers to take leading roles in planning and development of agricultural practices.

Naturally, not all users will be able to take individual responsibility for O&M. But the farmers using water should feel that the organization represents them well, protects their rights and benefits, and gives them a say, even directly through management decisions. The institutional body operating the irrigation facility should meet the requirements of the users and enable optimum use of the resources. The basic needs may be summarized in the following questions:

- What is the most suitable management body to operate the irrigation facility?
- What are the procedures to form a successful institutional body?
- How should the new organization arrange the functions of its various establishments and interconnections, split up duties and responsibilities, and secure coordination?
- How should the organization find financial resources for its activities?
- What is the procedure to follow for sustainable facilities?
- How can we ensure maximum benefit from the project?
- How can we reduce the project's adverse effects on the environment?

To evaluate water as a good, the government must give it a price, change the cost to the users, and create revenue. At present, SHW is not charging for the O&M

costs of the main systems or for irrigation water supplied to irrigation districts. Without collecting a sufficient charge for irrigation water, the districts will be unable to adequately develop their O&M.

The facilities should become the users' property, and they should repay the installation costs of the infrastructure. According to current laws, users cannot own a facility, and ownership and installation costs remain with the government. Some advanced countries establish water rights and the users own the water rights, which may be exchanged in the stock market. Turkey should consider the applicability of this system to its circumstances, which could turn out to be a basis for water sales.

Implementation

THE GAP MOM MODEL — PHASE I: DEVELOPMENT — The crucial work of formulating the MOM model took place in 1993–94, during phase I of the project. The project covered the broad model needed to encompass all the stakeholders and issues (Figure 1).

Six working groups, each comprising 17 experts, formed for the Workshop on Management, Operation and Maintenance, organized 6–8 December 1993, and the events of the conference were as following:

- Conference participants evaluated submodel options for development of the MOM model and compared their pros and cons.

- They discussed combinations for submodels, after deciding that SHW, an irrigation company, or a greater irrigation organization, must manage, operate, and maintain the main channel.

- Participants at the workshop evaluated 22 technical discussion reports on key issues and settled the key issues affecting the MOM model — technical, legal, institutional, environmental, and sociological issues, the availability of local water resources, and farmers' participation.

- Because no irrigation company is large enough to operate the main channel and a new irrigation organization would lack experience and be smaller than the irrigation companies, the participants abandoned these two alternatives and retained the SHW model as the best alternative.

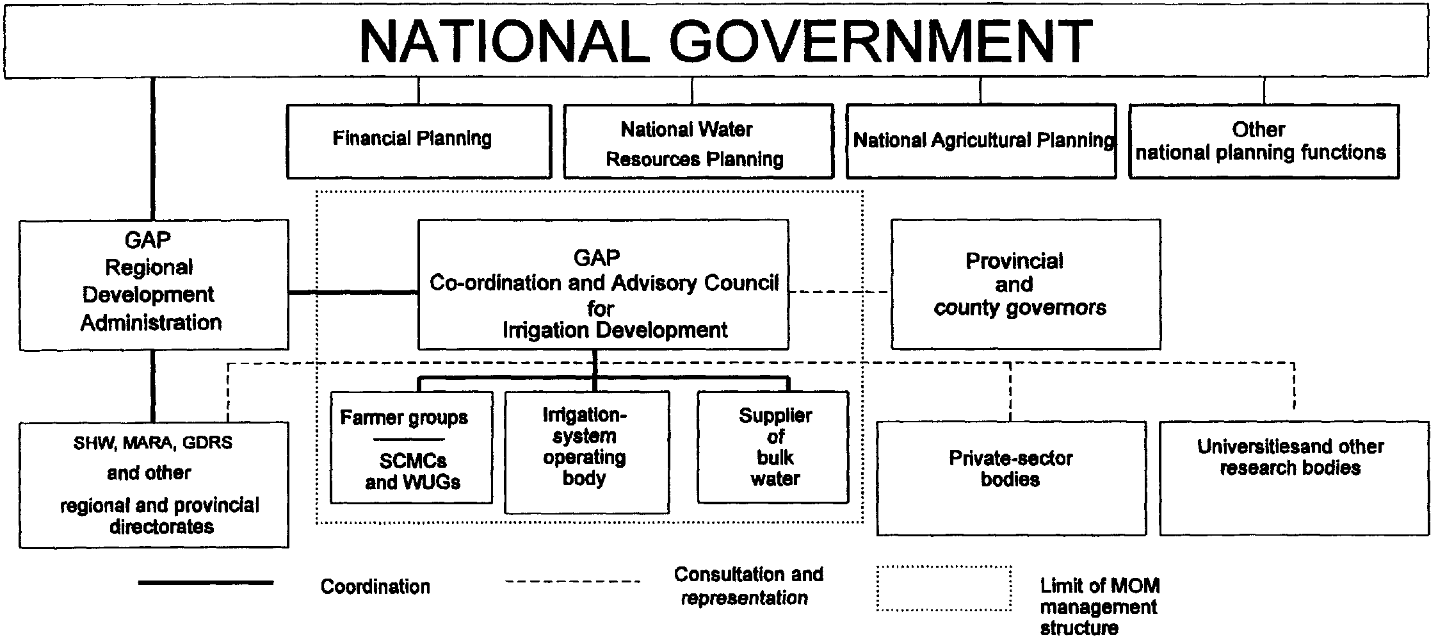

Figure 1. MOM institutional framework. Source: Internal documents of GAP Regional Development Administration. Note: SHW, State Hydraulic Works ; GAP, Güneydoğu Anadolu Projesi (GAP, Southeastern Anatolia Development Project); GDRS, General Directorate of Rural Services; MARA, Ministry of Agriculture and Rural Services; WUG, water-user group.

- Participants evaluated subalternatives for the SHW model to fully involve SHW in the MOM system:

  - If SHW keeps responsibility for the main and secondary channels and transfers only the tertiary channels to the irrigation districts, the government would save 45%.

  - If SHW keeps only the source (that is, the dam) and transfers the main, secondary, and tertiary channels to the irrigation districts, the savings would increase to 61%, with 75% of this obtained through transfer of MOM activities to irrigation districts on tertiary channels, alone.

The workshop participants determined that the government would obtain the highest savings through the transfer of MOM responsibilities for the tertiary channels to the beneficiary groups (irrigation districts) (GAP–MOM Working Group 1993;[1] GAP 1994[2]).

To develop the model, the participants considered many subjects and disciplines within the political, economic, social, technical, environmental, and legal environments:

- Water-distribution organizations and management methods for various water-supply systems;

- Existing organizational arrangements in the agricultural sector of Turkey and their efficiency and appropriateness for the GAP project;

- Regulatory and legal aspects of water-supply management, water use, land ownership, and the farmers' organizations;

- Sociological issues, such as social and family structures, variety of work, farming applications, cultural preferences and differences, level

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[1] A number of reports based on the research carried out by a group of experts in the framework of GAP–MOM in 1993.

[2] A group of experts (working group) who carried out their studies all throughout a year or two and circulated their reports in the department. 1994. Management operation and maintenance of GAP irrigation systems. An internal document of GAP. Identification report. Vol. 1, Oct. Printed in Şanlıurfa, Turkey.

of understanding of irrigated agriculture, training needs, and the characteristics of water users;

- Technical factors, such as the use of canals or pipes for the distribution system, irrigation methods, cropping patterns and intensity, soils and topography, drainage needs, availability of water resources, and operation methods for large drainage and distribution systems;

- Microeconomic issues at the farm level, such as alternative crops, cost of inputs (including water charges, product pricing, and farmers' budgets), and marketing policies;

- Microeconomic issues for the irrigation management organizations, such as water-charge structures and policy, cost of finance, and possible economies of scale and their impacts on O&M costs;

- Macroeconomic factors at national and regional levels; and

- Environmental problems and the controls to minimize their negative effects on the water and soil resources and human health.

The model in Figure 1 shows a framework of stakeholders and how they can work together to deliver a successful irrigation-development program. At the core of the model is the group of organizations managing the three levels of irrigation system. At the bottom level are farmers' groups, irrigation system-operating body, and the supplier of bulk water. The size of the model does not match that of the scheme. Where the scheme is small it is possible that more than one function will be carried out by a single organization, such as supplying bulk water and operating the irrigation system.

The model involves a bottom-up participatory approach at the farmer-groups level. It provides a framework for fair water distribution and WUE, leading to sustainable production techniques that protect soil and water resources. It requires clear boundaries of responsibility and liability among the three levels. This has to include the concept of delivering an agreed level of service at that boundary in return for a financial consideration across the boundary. The model allows the management organizations financial and decision-making independence, and in this way it maximizes their responsibility and accountability.

THE GAP MOM MODEL — PHASE II: REFINING AND TESTING THE MODEL — Since completion of phase I of the GAP MOM project, SHW has completed new irrigated areas, and irrigation districts have formed. The Harran Plain of GAP, for example, has 107×10^3 ha under irrigation, 16 irrigation districts, and new irrigation districts on the way.

A steering committee, with representatives from organizations, has been formed to make the necessary decisions concerning implementation. The committee has played a considerable role in the success of the project.

Phase II of the MOM project started in late 1997 and has had to take these recent developments into consideration. The project is using one irrigation district in the Harran Plain, which has 600 farmers, as a pilot area (pilot area 1) to investigate ways to improve the establishment and operation of these organizations. It is also studying how best to involve lower level farmer groups in new irrigation districts.

Findings to date show that the lack of any background or history of irrigation in the area has led to misunderstandings concerning the distribution system. The speed of the transfer process, which allows farmers and operators little opportunity to assimilate their new environment, has compounded the problem of misunderstandings. It is also evident that the coordination between departments involved in irrigated agriculture could make significant improvements. Coordination is currently weak and a constraint to speed and efficiency.

Farmers have ignored the scheme's fairly low irrigation modulus. More correctly, the farmers probably never understood the implications of the low modulus, if indeed anyone explained it to them. Farmers have subsequently started cultivating large areas of cotton, which has water requirements in excess of system capacity. The ensuing problems with the distribution of water led to a situation in which irrigation district, farmers, and the agency responsible for design and construction were blaming each other for the apparent but unproven deficiencies in the system. Lacking even a rudimentary system of monitoring of discharges in the distribution system for which the irrigation districts were responsible, they were unable to accurately locate its constraints and were thus unable to formulate any solution.

The MOM project has monitored canal and drain flows for the early part of the 1999 irrigation season and checked the locations where system capacity was of concern. The project has developed and is now testing simple water allocation and distribution procedures. The rules dictate that the bulk supplier (SHW) deliver discharges to each of the off-takes managed by the irrigation districts, based on estimated crop water requirements. For peak season, the project uses a proportional distribution method based on gross irrigated area.

Work is also currently underway within the pilot area to test water distribution-planning tools to allow the farmers in the secondary and tertiary systems to plan rotation schedules and allocate water equitably among themselves.

The project is using these early studies and trials to develop manuals for irrigation district O&M. These will, if replicated in all the districts in the scheme, provide the basic tools and rules to manage the system. The lack of such comprehensive instructions has so far been a tremendous demoralizing hindrance to the technical staff of the districts. The project is developing a management manual, concurrently with an O&M manual, that bring together the relevant methods and procedures under the laws governing the irrigation districts. The manual outlines a comprehensive information system, including accountancy practice, purchasing procedures, administration of maintenance works, and systems for water-charge collection. It also covers the district's need for sensible strategic planning, and the project is developing a system of annual work plans and 5-year plan to enable districts to manage their finances effectively, carry forward savings, and develop the services their members need. The procedure is now in the embryonic form of an asset management process to be developed further as the organizations gain experience and capability.

Modifying the transfer process

Analysis of the situation in a newly formed irrigation district has shown that the region's limited ability to manage irrigation requires a new approach to forming irrigation management organizations such as irrigation districts.

Under the GAP MOM project, a participatory process has been outlined and proposed. The project is now testing it in a second pilot area in GAP (pilot area 2), which has 300 farmers. The second pilot area is 2.5×10^3 ha within a piped irrigation scheme of 19×10^3 ha. An outline of the participatory process is shown in Figure 2.

The process is based on the early introduction of the farmers to the system design. Planners use their input into the design process, wherever technically feasible, to improve the layout, so that it genuinely meets the requirements of the field layout and farmers. Where land consolidation is required the same farmer participation will assist in speeding up the consolidation process and ensuring that the scheme layout and consolidated land holdings are compatible.

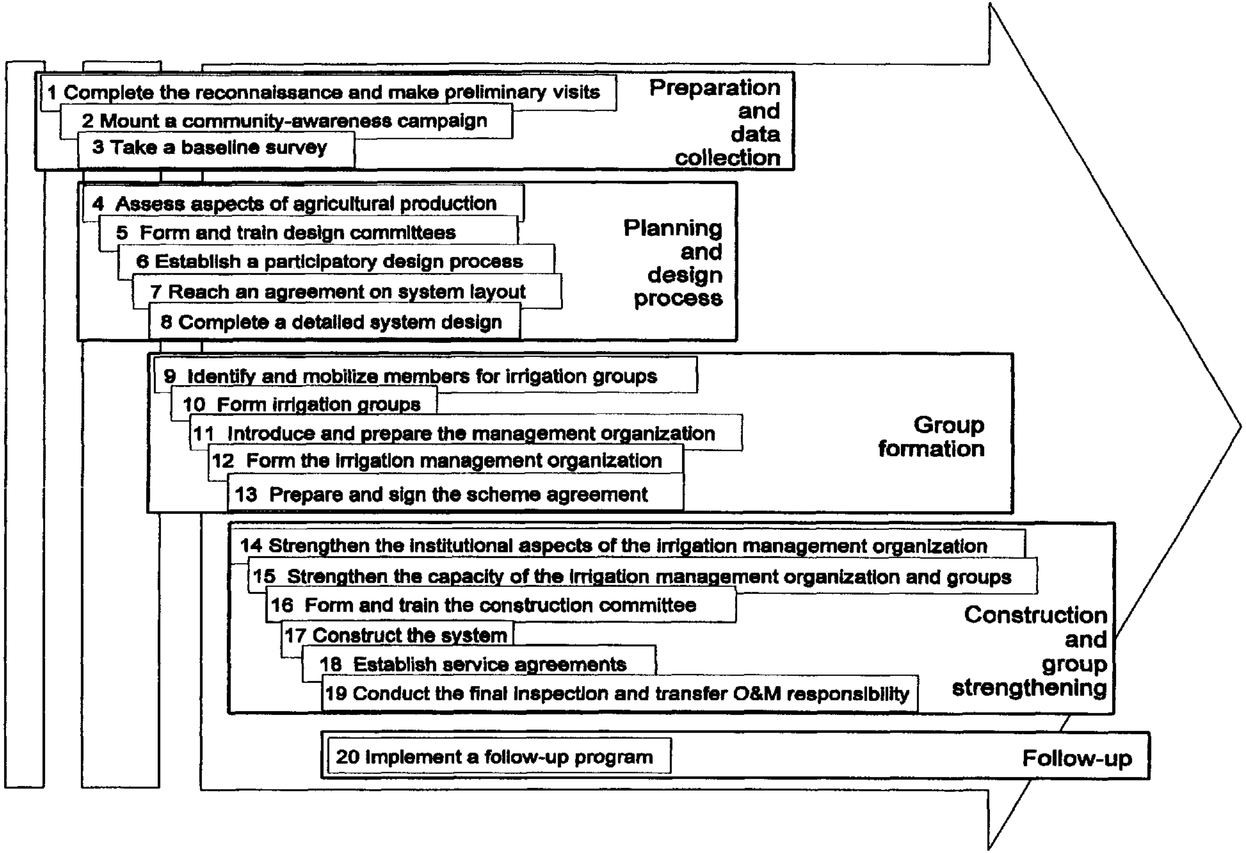

Figure 2. Participatory processes. Source: Internal documents of GAP Regional Development Administration. Note: O&M, operation and maintenance.

The results of the trial are eagerly awaited. It is anticipated that by increasing early awareness of the beneficiaries to the scheme and to what it will offer them, the project will reduce the problems experienced in the Harran Plain. In effect the farmers will be ready and responsive when irrigation commences, both in the field and in the management organization they establish.

Regulatory requirements

The project is studying the regulatory requirements, in parallel with the work on the irrigation-district MOM procedures. Irrigation districts are established under municipal laws, at the request of the scheme developers at SHW. The resulting organization is effectively a branch of local public administration. The political forum, as depicted in Figure 1, is therefore still current, but perhaps reduced to the extent that the organization's revenue from service charges is solely for irrigation within the irrigation district. Irrigation districts are subject to municipal laws, and the Ministry of the Interior is responsible for inspection of procedures and performance. These regulatory procedures cover economic aspects of the business. The district management manual incorporates the requirements, so that it is clear to the irrigation staff what their responsibilities are.

Technical regulations are harder than economic regulations to enforce. Irrigation districts have an obligation to distribute water to farmers equitably. Having the political forum within the organization can lead to partiality in water deliveries, favouring certain areas of the distribution network. To achieve an impartial delivery service, the districts need to isolate their staff from their political elements. Municipality laws on employment terms and rules currently allow for this, but they are inadequately enforced. Because they have inadequate protection, staff members are reluctant to correct inequitable distribution when it arises. The increases in water charges needed to cover the current cost of maintenance are almost impossible to implement with these low levels of openness and quality of service.

The technical difficulties of monitoring to ensure equitable distribution are also many. The government designed the distribution networks when it had the management role. Therefore, the design sometimes failed to consider the need to measure discharge on the scale required for the new operating environment. An accountable management must have adequate information to make good operational decisions. Unfortunately, the design of schemes is lagging behind the change in management structure, and schemes do not have good facilities yet to measure discharge.

Regulations, if carried out effectively and diligently, would help to identify such constraints. The scheme development process can feed identified needs for improvements back into its earlier stages. In the long term, the project expects to make significant improvements in efficiency and quality of service available to irrigators.

Because of the continued presence of the political forum within the organizations at the lower levels, those implementing regulations would need to take a very sensitive approach. It would also require championing and leadership to convince the beneficiaries of the irrigation systems to accept regulations. Political backing for the regulatory process would be a prerequisite for its success.

Training and demonstrations

Altogether the pilot areas have 900 farmers, with 600 in pilot area 1 and 300 in pilot area 2 (Tables 4 and 5).

Impacts of MOM model

Impacts of the MOM model have been as follows:

- Tertiary-level water savings are possible with planned water distribution. In trial areas, the model achieved a savings of 11% over the existing local distribution plans.
- Using gated pipes achieved water savings of 20–25% at the farm level.
- Crop rotation increased vegetable production area to 134 ha, or 2% of irrigated areas.
- The income of farmers growing vegetables in rotation increased 5–15 times that of cotton growers.
- Growing vetch as green fertilizer has increased the cotton yield.
- Crop intensity increased up to 170% in demonstration areas and an average 110% in the irrigated areas of Harran Plain.

Table 4. Technical personnel training.

Topic	Trainees	Number of trainees
Irrigation, drainage, water management, O&M, extension, general agricultural practices	Group organizers	7
Irrigation, drainage, water management, O&M, extension, general agricultural practices	Irrigation-district secretaries general, agricultural engineers in extension services, researchers	23

Source: Various circulated research notes of the Management, Operation and Maintenance Working Group.
Note: O&M, operation and maintenance.

Table 5. Farmer training and demonstrations.

Topic	Number of farmers
Irrigation, vegetable growing, crop rotation, O&M, water management	450
Practical on-farm training and demonstrations	23

Source: Various circulated research notes of the Management, Operation and Maintenance Working Group.
Note: O&M, operation and maintenance.

Lessons learned

Lessons learned from the project have been as follows:

Management

- SHW must provide appropriate procedures, guidelines, and manuals (as vital support tools for the new organizations or for existing organizations learning to fulfill new roles);

- Despite the planners' use of an inappropriate law (to expedite O&M handover), they failed to adjust the level of the support for implementation to ensure application or development of appropriate procedures.

- Current legislation allows elected officials (from the local community) to manage the salaried professional and technical staff, although they do not necessarily have the technical qualifications or experience to do this.

Operation

- It is important to involve the farmers at an early stage of scheme to establish good operational methods at the start (this helps prevent the introduction of bad habits and unfair practices of powerful or influential irrigators).

- At the design stage (it is easier, cheaper, and more accurate), the system should incorporate the needs of the participatory management (for example, more measurement structures).

- The farmers should have economically sound, practical, hands-on advice.

- It is vital to ensure adequate investment in the people (training, benefits, etc.) at an early stage, preferably before starting to operate and collect revenue. Start-up funds (working capital) should be available for this.

- Independent monitoring should be in place for organizations responsible for O&M.

Maintenance

- "The infrastructure is new, therefore if it was properly constructed, why should it need maintenance?" If someone is asking for maintenance, then clearly the quality of construction was inadequate, and it is the constructor's responsibility to correct this inadequacy.

- Understanding the concepts of depreciation and planned investment in maintenance and asset development requires extensive time and training.

- Irrigation districts have few checks or inspections to determine whether they are fulfilling their obligations.

- Currently no rules or laws allow or encourage irrigation districts to account for depreciation and have funds available to maintain their assets. Furthermore, the skills of irrigation-district boards and staff are inadequate to the task, and they need a long-term skills-development strategy and -asset management plan. This will, or should, involve changes in legislation to help drive the needed changes in attitude.

- The lack of inspection and controls on irrigation districts or subsequent action to rectify problems has allowed them to develop poor water charge-collection ratios. This has led to shortages of funds for all business except that most important to the chair and the board. This has not generally included asset maintenance. Urgent requirements are additional control and the political will to act to force monopolistic irrigation districts to improve standards of service.

Scheme development

- To introduce a more participatory approach would require implementing departments to undertake a more detailed coordination of activities and give a formal role to a coordinator or manager.

- The participatory approach has highlighted the budget problems, and having to work piecemeal has dampened the farmer's enthusiasm for the irrigation project.

- When fully tested this approach will reveal a need for greater analysis of economic factors, the cost of the capital recovery to the farmers and irrigation districts, and the O&M costs versus the ability of the farmers and districts to pay. Under the law governing SHW, the irrigation districts cannot use the revenues from service charges but have to pass all funds onto central government, and thus can take no advantage of a buyer–supplier market-type interface.

Conclusion

That transferring irrigation management to users would reduce the financial burden on government is well known. Governments have many strategies for implementing the transfer that they have tried at various times in various industries around the world. Turkey has followed the route of management transfer for its expansive network of irrigation systems. It has achieved this with remarkable speed and success, mostly on existing schemes.

GAP has developed a model to encompass all aspects of the MOM of irrigation in a region where the area under irrigation is rapidly expanding. Recent experience in the region has shown that the participatory approach of developing the irrigation management organizations at the lower level of the irrigation system is correct. The farmers' lack of experience with irrigated agriculture and irrigation management means that they need to be involved early in design and development to avoid constraints and bottlenecks in the program.

The MOM model encompasses all aspects of the irrigation process needed to ensure integrated and sustained development of irrigation in GAP region. The project has taken the model in broad outline, refined it, and identified the operational requirements for implementing it at the irrigation-system level. It has been testing operating methods and procedures developed in two pilot areas. The development of irrigation in the region has been so dynamic that the model needs further refinement. Legislators must consider regulatory requirements with this in mind and design the regulatory system to allow planners to refine the model.

Programs in the near future will implement new procedures. These will have to consider the training requirements of existing and new irrigation management organizations. The training process will have to include the scheme designers and developers, as well as the organizations and departments responsible for regulating the irrigation management organizations. The implementation program will require funding. It can use government funds, but in the short term this adds to the financial burden on the state. Alternatively, the program could raise funds wholly or in part from the irrigation management organizations themselves. Although this would help ensure their commitment to improving management performance in the irrigation sector, it would mean increases in the irrigation water charges. Such increases are a sensitive issue and may make the program impossible to implement without a strong political will to ensure progress and success.

Prerequisites for sustaining and extending the GAP MOM project are the following:

- Political support must continue;
- Other public bodies must contribute to the project;
- Public institutions must participate in the planning;
- Related master plans must be in place; and
- The project must have the benefits of institutionalization.

If an independent consulting firm or department carries out the evaluation and monitoring of the project, this would ensure greater objectivity.

Reference

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Chapter 8

DESIGN AND MANAGEMENT OF IRRIGATION SYSTEMS

THE SOUTHEASTERN ANATOLIA DEVELOPMENT PROJECT

Ayşegül Kibaroğlu

Introduction

Population and economic development have overwhelmed traditional water management practices in the eastern Mediterranean. Water management issues can conveniently be considered under two major headings: supply management (to locate, develop, and manage new sources); and demand management (to promote desirable levels or patterns of water use). Given the constraints on new supplies in the region, it should place far greater emphasis on demand management. To adapt themselves to limited availability and growing demand for water, countries in the region can stress the productive efficiency as a major goal for water use, along with the principles of efficient allocation. Hence, a realistic approach to the water problem in the region should incorporate policies to improve management and allocation, and it should also upgrade and modernize water-delivery structures in major sectors of the economy, such as agriculture.

Demand management covers both direct measures to control the use of water, such as technical interventions in all sectors to reduce water losses and the modernization of both the distribution and on-farm systems, and indirect measures such as water charges, tariffs, market mechanisms, financial incentives, and public education, affecting voluntary behaviours.

Because irrigation accounts for some 75% of water withdrawals region wide, technical interventions to reduce water use have significant potential in irrigation. Hence, many experts recommend promoting irrigation water-use efficiency (WUE) as the essential strategy to address the problems of water scarcity and the high cost of new supplies. Technological and managerial demand management options are available to improve irrigation WUE. Traditional irrigation technologies, which usually rely on gravity to deliver water to plants, have substantial water losses and poor uniformity of distribution. Modern technologies, such as sprinkler and drip irrigation systems, are major water-saving techniques that improve WUE. Technological improvements in irrigation systems have expanded production opportunities.

This study will therefore look at the Turkish experience in using technological and managerial options to improve irrigation, with special attention to the developments in the Güneydoğu Anadolu Projesi (GAP, Southeastern Anatolia Development Project). GAP is unique, as a transboundary river system is the major source for irrigation in the project area, namely, the Euphrates and the Tigris rivers. Hence, improvements in the patterns and levels of use and management of water resources would not only increase WUE at the national level but also support policies to stretch these transboundary water resources to meet the growing demands of coriparians. More importantly, experiences gained from GAP will challenge the existing water-use and management practices of coriparians, in Iraq and Syria.

The agricultural area of Turkey is huge (around 28×10^6 ha), but the productivity is surprisingly low because of the aridity, along with factors such as farmers' persistent use of traditional on-farm practices. Government policies aim to expand the area of irrigation to tackle the problem. An estimated 8.5×10^6 ha of land is economically irrigable.[1] By the end of the 1990s, Turkey had developed half of this potential (that is, 4.16×10^6 ha). Although Turkey is self-sufficient in water resources, the water is not always in the right place at the right time to meet its current and future needs. Its uneven rainfall distribution makes irrigation infrastructure indispensable. For years, Turkish governments have pursued a strategy of low-cost rapid expansion of irrigation (gross irrigated area doubled within 30 years from 2.3×10^6 ha in the 1970s to 4.16×10^6 ha in the 1990s). The primary aim has been to make more land irrigable as quickly as possible, although that has meant facing problems of modernization later on.

GAP, being Turkey's largest multipurpose integrated development project, plans to add 1.7×10^6 ha to the 4.16×10^6 ha currently under irrigation. Along with initiating the major irrigations of the GAP region in 1995, especially in the renowned Şanlıurfa–Harran Plain, it has tested various irrigation technologies to ensure planned development and efficient use of limited water resources. Hence, the project has planned to expand the irrigated area while adopting modern irrigation technologies. Land and water are the major natural resources and they are the driving force behind the GAP. Thus, the project aims to achieve economic and

[1] A number of prominent scholars from the faculties of agricultural engineering have emphasized that the gross irrigation potential in Turkey is 12×10^6 ha. Indeed, the amount of irrigable land in Turkey would be much higher with modern technologies and land leveling (personal communication, Prof. Dr Osman Yıldırım, Faculty of Agriculture, Ankara University, and Prof. Dr Osman Tekinel, President, Kahraman Maraş Sütcü İmam University, April 2000).

social development through making optimum sustainable use of these resources. To achieve this goal, GAP has been implementing various projects, with a view to attaining appropriate use and management of available resources.

At present, 327 x 10^3 ha of land is under irrigation in the GAP region. Irrigation projects in the GAP region are the most important part of irrigation development. Considering that water is the most important input needed to increase agricultural yield, the project aims to use this resource as efficiently as possible. Thus, GAP has been testing four irrigation methods on a pilot area of 3 × 10^3 ha in the Şanlıurfa Plain to compare their water savings: pressured irrigation, low-pressure irrigation, unit area and unit water, and classical canalette network. This study will examine the implementation stages and the impacts of this project. However, the analysis will also rely on other primary projects on land–water resources in the region, such as the Project on the Management–Operation–Maintenance (MOM) of GAP Irrigation Systems. Interviews with authorities in the GAP administration emphasize that sound research depends on a joint evaluation of major projects because they all aim to ensure the sustainable use of natural resources.

GAP: an overview

The construction of three major dams on the Euphrates — Keban (1974), Karakaya (1987), and Attar (1992) — originally planned as a part of the Lower Euphrates Project, initiated GAP, the most ambitious development scheme in Turkey in 1980 (MENR 1966).

The intention of GAP was basically to harness the waters of the Euphrates and Tigris rivers for hydroelectric power generation and irrigation (MENR 1980). However, it later became a multisectoral development project covering all sectors related to development, such as agriculture, industry, transportation, urban and rural infrastructure, health care, education, housing, and tourism (Ünver 1993).

The GAP project area lies in southeastern Turkey, covering nine provinces, with about 10% of Turkey's total population and a surface area of 75 x 10^3 km^2. The project area includes the watersheds of the lower Euphrates and Tigris rivers and the upper Mesopotamian plains. The GAP water development program includes 13 large subprojects altogether, 7 of which are on the Euphrates river — Lower Euphrates, the largest and the most comprehensive project, including the Atatürk Dam and the Şanlıurfa Tunnels, together with 5 more subprojects within this framework (Karakaya, Euphrates Border, Suruç–Baziki, Kahta–Adıyaman, Gaziantep, and Gaziantep–Araban) and 6 on the Tigris (Dicle, Kralkızı [under construction], Batman, Batman–Silvan, Garzan, Ilısu, and Cizre). The GAP involves a total of 21 major dams and 19 hydroelectric stations, as well as irrigation networks to irrigate 1.7×10^6 ha of land. The centrepiece is the Atatürk Dam, completed at the beginning of the 1990s, with a storage capacity of 48.7×10^9 m^3, and an installed electricity-generating capacity of 2.4×10^3 MW (Bağış 1989, see especially p. 52).

Other major works in GAP are the Şanlıurfa Tunnels, the Birecik and Karkamış dams on the Euphrates, and Ilısu on the Tigris. The Şanlıurfa Tunnels are the major units of GAP, two tunnels that discharge water from the reservoir of Atatürk Dam at a rate of 328m^3/second. Water reaches the Şanlıurfa–Harran plains via Şanlıurfa Tunnels, two parallel tunnels, each 26.4 km long. One of the tunnels opened in 1995, and 9×10^4 ha was under irrigation in 1998. The Şanlıurfa–Harran Plain has two main canal systems. Şanlıurfa Main Irrigation Canal will use a gravity-driven method to irrigate 43×10^3 ha and a pumping method to irrigate 5×10^3 ha. The Harran Main Irrigation Canal will use a gravity-driven method to irrigate 98.5×10^3 ha by gravity.

People consider GAP a very expensive project: an estimated $32 billion (United States dollars throughout), of which the project has so far spent only $13.9 billion. Because the issues involve transboundary flows, it has not been possible to secure international finance, except for the German and Swiss credits for equipment purchases and some others. The World Bank requires the "consent" of all the parties riparian to a transboundary watercourse on the project to develop a portion of the river. GAP is very critical for the Turkish economy. With a planned installed capacity of about 7.5×10^3 MW and a hydropower-generating capacity of 27 GWh annually, it will significantly increase the country's existing energy output. Turkey has a huge demand for hydropower, as a result of its population growth (2.2% per annum), urbanization (3.6% for 1985–90), and impetus for industrialization. Moreover, with the envisaged irrigation systems, Turkey is determined to develop agriculture and agroindustrial production for export and raise the living standard of people in the region. The importance of GAP for Turkey can be summed using two sentences: GAP will add 70% to Turkey's existing hydroelectric output and 1.7×10^6 ha to the current 4.16×10^6 ha of irrigated land. Turkey currently has 327×10^3 ha of land under irrigation in the GAP region. Whereas the state has irrigated 211×10^3 ha of this total, private irrigation accounts for 116×10^6 ha.

Starting in the late 1970s and early 1980s, researchers have conducted numerous studies on the characteristics of the water and land resources in the GAP region, in general, and the Harran Plain, in particular (Ayyıldız et al. 1986; GAP 1993). These studies classified the soils in the GAP region into eight capability classes, defined according to soil texture and depth, water-holding capacity, alkalinity, salinity, topography, stoniness, and drainage. More than 90% of the land belongs to class II, which were highly suitable for agricultural use. However, these studies emphasized that soils in the region comprise mainly silty clays. Hence, they pointed to the danger of applying excessive water which may create cracks in the soil and extensive waterlogging in the region.

In addition, these surveys showed that salinity and alkalinity are not widespread problems. They indicated stoniness is a major problem in the region, and stone clearing has been a major operation in farming areas. Primarily, low wind speeds in the region have limited wind erosion. However, these studies indicated that soil erosion from running water has been serious in the GAP region, particularly on sloping ground, where you find reduced vegetation cover.

Given the underdevelopment of the southeastern Anatolia region and the government's desire to raise the population's standard of living, the importance of GAP to Turkey is obvious. The GAP region faces many of the problems typical of underdeveloped regions. Compared with the rest of Turkey, it has had higher fertility, higher infant mortality, and lower literacy rates because people there have less access to health care and education. The region also experienced a net out migration, both seasonal agricultural migration and permanent rural-to-urban out migration, as a response to high unemployment. The region's economy depends largely on agriculture, but its productivity has historically been low. In 1985, per capita income in the region was half of the national average, and the region accounted for only 4% of the GNP, although it has 10% of the country's area and population (Ünver 2000).

Nipon Koei Co. Ltd and Yüksel Proje A.S. (1989) carried out a master-plan study to determine the region's potential for and bottlenecks to development and to set the development objectives and strategies in general and in sectors related to development. Among the development objectives of GAP are

- To raise the income levels in the GAP region by improving the economic structure and thereby narrowing the income disparity between this and other regions;
- To increase the productivity and employment opportunities in rural areas;
- To enhance the assimilative capacity of larger cities in the region; and

- To contribute to the national objective of sustained economic growth, export promotion, and social stability with efficient use of the region's sources.

The project plans to develop the region's soil and water resources to provide a basis for agricultural development, with substantial increases in production output, diversity, and productivity, which will stimulate the growth of the agroindustries.

Sustainability of irrigation in the GAP

The master plan for GAP called for a new entity, namely, GAP Regional Development Administration, to manage, monitor, evaluate, and implement development. RDA defined the expanded principle of sustainability for GAP's holistic approach, which covers several aspects of sustainability:

- Sustainability of irrigation;
- Sustainability of the agricultural system;
- Economic sustainability (or economic feasibility);
- Environmental sustainability;
- Spatial sustainability (that is, sustainability of land use and transportation); and
- Societal sustainability.[2]

In accordance with GAP's sustainable development approach and strategies, it has initiated special programs and projects, with a view to emphasizing the human dimension of development through basic social services. The design, construction, management, and operation and maintenance (O&M) of irrigation facilities are essential to these social services. Irrigated agriculture is the basis for the sustained development of the GAP region. The master plan and the subsequent studies of the GAP RDA stress the principle that the use of the irrigation system should be sustainable. Land and water are major natural resources and form the driving force

[2] Interview with Dr Olcay Ünver, President of the GAP RDA, General Directorate of GAP RDA, Ankara, 30 Mar 2000.

of GAP. The project aims at economic, spatial, and social development through the optimum and efficient use of these resources according to the principle of sustainability.

GAP has implemented four major projects to ensure planned development and effective use of water resources in the irrigation subsector. As a whole, these on-going projects serve the primary aim of GAP for surface (Tigris and Euphrates rivers) and groundwater resources of introducing technological and managerial measures to improve the efficiency of the irrigation subsector. GAP drafted its master plan to ensure efficiency and integration in the use of the land and water resources of the region. Hence, the basic development scenario the plan envisages is to transform the region into an agriculture-based export centre. These four projects are an essential part of the following package of agricultural development projects and activities (Ünver 1999):

Projects on land–water resources

- Land consolidation;
- GAP agricultural research-and-development project package;
- Projects for agricultural marketing, crop-design planning, and integration of marketing and planning works;
- Study on agricultural-mechanization needs in the GAP region;
- Economic analysis of enterprises in the GAP Region and their short-, medium-, and long-term credit needs;
- GAP region fresh vegetable and fruit postharvest technologies;
- Projects for raising the income level of people in nonirrigated areas;
- Afforestation and erosion control;
- Şanlıurfa–Harran Plain on-farm and village development project; and
- Feasibility study on Ceylanpınar groundwater reserves.

Projects in the irrigation subsector

- Improvement of irrigation-canal regulatory schemes in the GAP region;
- Comparative study for various irrigation methods and techniques;
- Introduction and demonstration of new irrigation technologies; and
- MOM of irrigation systems in the GAP region.

Projects to improve the design, management, and O&M of conveyance, distribution, and on-farm irrigation systems in the GAP region

Improvement of irrigation-canal regulatory schemes

The overall aim of the project to improve irrigation-canal regulatory schemes has been to improve conveyance, distribution, and on-farm irrigation facilities and thereby achieve efficient patterns and levels of water use in the GAP region. The GAP RDA and the French Water Management Department jointly conducted research to design and compare various regulatory schemes in the main irrigation (feeder) canal of GAP, the Harran Main Irrigation Canal, and select the one appropriate to meeting the following objectives (Ünver and Voron 1993):

- To prevent water loss or temporary shortages resulting from uncertainties in water demand from the heads of secondary networks;
- To take account of progress in canal construction (56 km of which was already complete), where GAP could modify only the type and characteristics of the regulators;
- To pay special attention to O&M criteria; and
- To consider the current state of local technical capabilities and ways to evaluate them.

GAP tested various regulatory schemes on the Harran Main Irrigation Canal, the largest and longest (118 km) of its kind in Turkey. The Atatürk Dam reservoir feeds the Harran canal through the Şanlıurfa Tunnels. It has a design capacity of 80 m^3/second and provides water to irrigate an area of 141 × 10^3 ha. Certain options were analyzed to design a regulatory scheme with minimal water losses, easiest to operate, and economical. The most appropriate scheme was a mixed regulatory system, with an upstream control section (first 56 km), a transition section, with in-canal storage (mid-18 km), and a downstream control section (last 44 km).

The mixed regulatory system of the Harran Main Irrigation Canal introduced, for the first time in the entire Turkish irrigation system, the "downstream control," with special emphasis on the water-on-request system. In Turkey, regulators commonly maintain irrigation facilities at constant upstream level. State Hydraulic Works (SHW) operates all main canals, whereas irrigation management organizations (that is, the irrigation unions) conduct the O&M of the existing systems at the secondary and tertiary levels. Secondary canals carry water from the main canal to the head of the irrigation scheme, whereas tertiary canals convey water from that level to the farm. Generally upstream control requires a rotation system to enable the continuous use of flows 24 hours a day. However, in most cases the operator does not make steady use of the rotation system on the tertiary canal and must allow an extra discharge to be sure of meeting demand if no accurate schedule of water requirements for the following weeks is available. This system leads to overuse of water resources, which in turn results in improper irrigation of fields. This leads to excess water and direct flow into the drainage network, with increased direct and indirect return flow.

Moreover, in the specific case of the GAP, rational and optimal use of water resources is a prerequisite for sustainable development. The water resources of the GAP region will soon become a limiting factor, as the project opens larger areas to irrigation and rapidly develops large-scale hydroelectric schemes. Furthermore, as provinces grow, with higher standards of living, and as factories flourish, municipalities and industries will put greater demand on existing water resources. GAP also tested a mixed regulatory system to limit effluent water downstream of the perimeters. Control of pollution through an improved irrigation canal regulatory system would not only protect water and land resources throughout the GAP region but also minimize the negative impacts of use made beyond the national borders of the Euphrates–Tigris river system, which drains from Turkey and flows through Syria and Iraq. Improving the regulatory system on the Harran Main Irrigation Canal will help to create efficient patterns and levels of water use in the irrigation sector most in need of water.

Ünver and Voron indicated that the mixed regulation used for the Harran Main Irrigation Canal brings together the advantages of flexibility, water economy, and fairly low incremental construction costs. First, the downstream control of the last section prevents water waste; and the entirely automatic operation of the mixed gates makes the system extremely easy to use and reliable. Second, the mixed regulatory system gives the flexibility to handle variations in demand for water from the perimeters. Third, the evolution of techniques and the advantage of easier use of water for irrigators may lead the distribution network to become a water-on-request system. Fourth, it is possible to integrate changes in equipment and water-use method into the secondary canals without having to modify the main infrastructure. Finally, the operator can master this technical compromise with minimal technical training (Ünver and Voron 1993).

Comparative study of various irrigation methods and techniques

GAP is testing four irrigation methods on a pilot area of 3131 ha in the Şanlıurfa Plain to compare water savings. The methods tested are:

- Classic canalette (flumes) network;
- Unit area and unit water (which involves adapting surface distribution via canals and flumes. The basic principle is to apply a strict predetermined rotation system. Water is not applied at farmers' request but through organized distribution.);
- Low-pressure irrigation; and
- Pressurized irrigation.

GAP selected the Şanlıurfa Plain for the implementation (pilot) area with the aim of presenting the technical characteristics of each solution and examining the differences in perimeter management (Ünver, Voron and Aküzüm 1993). The soil and topographical characteristics of the pilot area were average for GAP irrigation schemes. The technical solutions developed for the pilot zone had been applied in other schemes in the GAP region. Through this implementation in the pilot zone, GAP studied the technical, economic, and operational merits of various irrigation-water management practices in the farmers' actual environment. The study based comparisons of these four major irrigation methods and technologies on the following criteria:

- One of the goals was to reduce water losses, at both distribution and on-farm levels. The irrigation technique GAP selects for the rest of its irrigation schemes should make optimum and efficient use of existing water resources to allow their reallocation to meet the region's other emerging water needs;

- The study was to compare the technical characteristics of the four methods (based on their individual components and their overall efficiency);
- The study was to compare their maintenance properties: that is, the method should leave sufficient freedom for farmers and reduce the need for operating agencies to intervene;
- Best solution should also have the acceptance of the farmers: any solution would have to conform to farmers' prevailing technological levels and reduce constraints in field distribution; and
- The technique should also suit the evolving patterns of crop design in the region.

In Turkey, gravity-driven irrigation, through standard canalette networks, is the most common irrigation method for large schemes, ranging from several thousands to several tens of thousands of hectares. GAP has used this method on 211 080 ha (Table 1) of state irrigation as well. In gravity-driven irrigation systems, the supply and distribution networks typically operate with upstream control through embanked, lined canals or canalettes. Farmers use furrow or classic basin irrigation methods on the farm. These open channels or canalettes with upstream control are often wasteful. Moreover, a certain amount of difficulty occurs in managing water distribution in these installations. This system requires careful planning to match farmers' water demand and the discharge delivered from the main canal. Upstream control usually requires delivery schedules, based optimally on field observations and crop data. But in many cases they are based on outdated manuals or design reports. Upstream control requires estimates of distribution and conveyance efficiency, as well as the transmission time, to determine the flow and timing of release at the headwork.

However, in line with the interim results obtained in the pilot project area, SHW has started to build a low-pressure irrigation network with downstream control through buried pipes over about 125×10^3 ha of land in the GAP region. Hence, all the irrigation schemes in Table 2 have closed distribution networks,

Table 1. Irrigation projects under construction.

Project	Area (ha)
Şanlıurfa–Harran (partial)	50 000
Kralkızı–Dicle	24 421
Batman (left bank)	18 750
Batman (right bank)	18 600
Belkis–Nizip	11 915
Adıyaman–Camgazi (partial)	6 430
Kayacık Plain	14 740
Bozova (pumped)	860
Samsat (pumped)	2 806

Source: SHW (2000).

with downstream control. This not only has less water loss than open gravity-driven installations but also creates fewer physical obstacles, as apart from the main canal, the distribution network is all underground. Moreover, the demand of the farmers, not release at the head of the network, determines pipe discharges. The networks remain under constant (low) pressure, making water available at all times. When GAP has fully realized its irrigation projects (that is, when it has fully equipped 1.7×10^6 ha with irrigation infrastructure), 35% of these irrigation areas in the region could have irrigation water from pressurized pipes. This rate compares favourably with 15 and 30% in France and the United States, respectively. Moreover, about 50% of the irrigation from the Atatürk Reservoir will be through pressurized pipes. Pressurized-pipe irrigation systems are under construction in Kralkızı–Dicle (24 421 ha), Batman (18 750 ha), Bozova (860 ha), Belkis–Nizip (11 915 ha), and Samsat (2 806 ha). Sprinkler methods have been in use only in limited groundwater schemes in Ceylanpınar (27×10^3 ha) and some minor schemes between Viranşehir and Kızıltepe. High evaporation rates and the wind conditions in the region, as well as financial and institutional difficulties, constitute major impediments to expansion of areas under sprinkler systems.

With a view to possible advantages of widespread pressurized-pipe system in the whole GAP region, SHW has started to implement low-pressure irrigation ("California") systems in schemes under construction. The project has planned to establish the California system initially in Mardin–Ceylanpınar (15 376 ha), and Gaziantep–Kayacık irrigation projects areas (14 740 ha). Although this system uses

Table 2. Irrigation projects in operation.

Project	Area (ha)
Hancağiz	7 330
Şanlıurfa–Harran (partial)	117 000
Hacıhıdir	2 080
Derik–Dumluca	1 860
Silvan I and II	8 790
Nusaybin Cag–Cag	7 500
Silopi–Nerdus	2 740
Akcakale (groundwater)	15 000
Ceylanpınar (groundwater)	27 000
Devegecidi	7 500
Suruc (groundwater)	7 000
Cinar–Göksu	3 580
Garzan–Kozluk	3 700
Adıyaman–Camgazi	1 000

Source: SHW (2000).

conventional gravity-driven flow to irrigate the fields, it offers higher water-use flexibility and enhances water savings in the perimeter, as the farmers operate the flow-limiter valves themselves. Low-pressure pipe irrigation is technically feasible in the GAP region. Systems using low-pressure buried pipes have water conveyance and distribution efficiencies as high as 90%, compared with 50–60% for earthen canals. Such systems prevent unnecessary losses, both from seepage and from evaporation.

Introduction and demonstration of new irrigation technologies

In virtually all cases, farmers adopt the technology that produces the greatest net income, within acceptable levels of risk and complexity. What is essential to rapid adoption of a new technology is to expose farmers to it through word of mouth farm demonstrations and ensure sound support from private-sector suppliers. Hence, with this project, GAP RDA aims to establish demonstrative farming enterprises and widespread use of water-saving irrigation methods and technologies in the region. Giving special priority to the farmers who depend largely on groundwater resources, GAP RDA rents the equipment needed to irrigate using sprinkler and drip methods, including special methods of surface irrigation, namely, gated pipe.[3] For instance, at some plots, where farmers use gated pipes, they have achieved water savings of 20–25%. Private domestic or foreign companies donated all the equipment to GAP RDA. In collaboration with other state agencies (such as SHW, the General Directorate of Rural Services, and the Regional Department of Agrarian Reform), GAP RDA regional personnel select "leader" farmers it deems most capable and interested in applying these technologies and installs one of them in a designated plot, near other plots under traditional gravity-driven irrigation. Moreover, GAP RDA supplies the farmers with agricultural inputs such as fertilizers. Furthermore, it provides the farmers with all technical and managerial assistance and other extension services. In this way, it has installed 11 demonstration units in various parts of the region, like Nusaybin, Batman, Silopi, Şanlıurfa, Akcakale, Bozova, Bismil, Derik, Kızıltepe, and Dicle University. The GAP RDA constantly monitors O&M of these demonstrative units. All in all, this project enables farmers to build the capacity to apply water-saving (pressurized-pipe) irrigation methods and technologies. And, as noted earlier, when the project is complete, 35% of the GAP region will have the advantages of pressurized-pipe irrigation. Meanwhile, the initiatives of GAP RDA are giving farmers the technical knowledge and experience needed to use pressurized-pipe irrigation methods. Yet, for now, farmers use these technologies in limited areas throughout the region. This is largely due to their lack of capacity and funds.

Project on the Management–Operation–Maintenance of GAP Irrigation Systems

GAP has achieved notable progress in planning, design, and construction of major irrigation-water infrastructure and distribution works in the GAP region. However, according to GAP RDA, the appropriate MOM of these large-scale irrigation systems is essential to sustainable irrigated agriculture. Hence, in the early 1990s, GAP RDA introduced the MOM model to identify suitable MOM arrangements to make optimal use of resources invested in irrigation development. With the MOM model, RDA envisages addressing many institutional and technical problems stemming from the prevailing structure and practices of management organizations for irrigation in Turkey (Alemdaroğlu 2000).

With an ambitious start, the MOM study envisaged identifying the most appropriate organizational structure for water users to undertake the MOM of the

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[3] Gated pipe delivers water in metered quantities from farm turnout or tube well to a series of furrows. Pipes are available in portable materials. Pipelines take the place of field ditches and convey water across uneven terrain, reducing the need for land-leveling. They also eliminate ditch losses, which results in considerable savings in water (USNWC 1973).

irrigation systems in the region. In line with this major objective, GOP designed the model to provide a framework for equitable water distribution and higher levels of WUE to protect soil and water resources. Hence, GOP conducted socio-economic studies on future participation of farmers in irrigation activities, as well as evaluation of the current technologies and practices for MOM of large irrigation systems in Turkey and other countries. Through these studies and others, GOP developed the preferred basic management model. The model comprises group organizations to manage the three levels of the irrigation system: SHW as the supplier of bulk water through the main canals, an Irrigation Authority as the operating body, and water-user groups at the bottom level (the secondary and tertiary canal level), with direct grass-roots participation in water management, decision-making, and finance. The model relies on a bottom-up organization of village-level associations of irrigators.

However, the implementation of the MOM model has remained limited. SHW has established 38 irrigation associations in the region, under its pragmatic approach. In Turkey, the existing local-government structures have created all the irrigation organizations, which have multiplied since the early 1990s. Hence, these organizations are not a product of any grass-roots movement. SHW staff members have been the major initiators and executors of the transfer program. Since 1993, with an accelerated transfer program, SHW has managed to transfer 1.5×10^6 ha of irrigation schemes to local administrations or irrigation unions, using an innovative form of transfer, where the irrigation scheme covers more than one local administrative unit (for example, village or municipality). The poor performance of many large government-agency irrigation schemes in cost-recovery, equity, efficiency in O&M, and repair of expanding systems spurred efforts to increase the area of surface-water schemes transferred to the irrigation unions.

Hence, one can already detect a series of problems, emerging in the rapid transfer process, complicating the future progress of the SHW program. These stem largely from the financial shortfalls and organizational weaknesses of the irrigation unions, which do not have a strong legal standing. Although existing municipal laws appear to provide a workable basis for the formation of the irrigation unions, their evolution increasingly creates the need for an establishment law, specifically for irrigation unions. Moreover, allowing water rights for irrigation unions to remain undefined in Turkey could be very costly for them. To overcome these problems, irrigation unions must interact constructively with government agencies and technical experts (Kibaroğlu 1999).

Although existing irrigation unions in the GAP region have all formed and operated according to the prevailing SHW model, two pilot projects have started in two irrigation schemes in the region — Frat Irrigation Union and Kayacık Irrigation Project (still under construction) — to improve the organizational structures of irrigation unions, along with conducting other studies to

- Enhance participation of irrigators in investment decisions and building new irrigation systems;
- Minimize the role of local administrations in creation of irrigation unions;
- Strengthen the democratic procedure in the formation of their governing bodies; and
- Support the creation of federations of the irrigation unions at the catchment level.

Conclusion

Turkey envisages irrigation of 1.7×10^6 ha of land in the GAP region to boost the agricultural production of land and water resources. Agriculture is, indeed, the leading sector to develop the region. For a long time, planners in Turkey thought the existing water resources of the region, especially the major surface-water resources — namely, the Euphrates and the Tigris — would supply enough water for irrigation. However, as a multisectoral, integrated development project, GAP emphasized the development of other sectors of the region, such as the hydroelectric industry and cities, which compete with agriculture for water. Moreover, the GAP region has made no exact calculation of the irrigation-water needs of its evolving crop design. This evolving crop structure (fruits and vegetables) will very probably need more water than planned from the existing water supply. Hence, the irrigation subsector should use water as efficiently as possible. Furthermore, the major water resources of the region — namely, the Euphrates and Tigris — constitute a transboundary river system, originating in Turkey and flowing through Syria and Iraq. Hence, the Turkish schemes are not alone in demanding water at growing rates. These precious and limited water resources also supply these other downstream riparians. Improving the productive efficiency of their irrigation sectors (the sectors receiving the lion's share of water resources) through national technological and managerial solutions would also ease the stresses on these transboundary resources.

Concerning the policy, management, and technological aspects, the irrigation subsector needs to make environmentally sustainable increases in productivity with improvements in technologies (modernization), management, farmer participation, and institutions and policies. To have maximum impact, programs should make improvements in all four dimensions simultaneously. The on-going irrigation projects discussed throughout the paper all by and large work on these four dimensions, with a view to improving patterns, as well as levels, of water and land-resource use in the region.

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Chapter 9

EFFLUENT REUSE FOR AGRICULTURAL PRODUCTION

Gideon Oron

Introduction

Scarcity of conventional sources of waters in arid and semi-arid regions has promoted the search for additional sources (that is, unconventional or marginal waters), such as deep groundwater, treated wastewater, and brackish water. Runoff water varies in time, availability, amount, and location and is therefore a nonstable source. Saline water comes in the form of drainage water from agricultural fields or occurs in deep fossil aquifers. Using saline water results in limited agricultural yields, but improved product quality (Pasternak and DeMalach 1987). Domestic treated wastewater is a fairly stable water source and has uses in agriculture, industry, recreation, gardening, industrial-plant cooling, and recharge of groundwater (Cromer et al. 1984; Oron et al. 1986; Burau et al. 1987; Asano and Mills 1990; Campos et al. 1998). Where people have advanced irrigation technologies and water-harvesting, they often use this source of water to reduce demand and satisfy water requirements. Furthermore, droughts, which often occur in the dry regions, amplify water management problems and require long-term measures to reduce the vulnerability of water systems and short-term measures to mitigate impacts of the drought. Water-resources management in arid and semi-arid regions is a complex, multifaceted task, because of the need to integrate many hydrological, environmental, economic, social, and managerial factors. The holistic approach is appropriate to providing all users of diverse sectors sufficient supplies of adequate water while ensuring environmental protection.

Using treated wastewater for agricultural irrigation is attractive for a series of invaluable consequences (Gamble 1986; Chang et al. 1990):

- Water shortage problems can be resolved;

- Disposal of large amounts can occur throughout the year, with or without storage (under distinct circumstances, the storage can be an extra treatment phase), with minimal environmental risk (Shelef 1991; Oron et al. 1992; Juanico and Shelef 1994); and

- Economic benefits due to the nutrients make the effluent a better fertilizer (Oron et al. 1986; Neilsen et al. 1989).

The purpose of current work is to examine the hypothesis that treated domestic wastewater would have minimal health and environmental risks for crop irrigation using subsurface drip systems. Subsurface drip irrigation (SDI) allows the soil surface to remain dry and minimizes contact with pathogens. The concept of using treated wastewater with minimal risks is based simultaneously on field experiments and complementary management analysis by defining an exposure-risk model (ERM) (Figure 1).

Materials and methods

Field studies

The experimental site

Field experiments are in progress in the commercial fields of Kibbutz Chafets-Chaim (a cooperative farm) in Israel. Mean annual precipitation is around 600 mm from October until March of the next year. Mean minimal ambient temperature is around 8°C during January and around 17°C during August. Mean maximal temperature reaches 20°C during January and 31°C during August. Maximal class-A evaporation is around 8 mm/day (Figure 2). The soil in the experimental site comprises about 36% clay, 17% silt, and 47% sand.

The crop

Cultivation in the commercial fields uses conventional crop rotation, including cotton, corn, wheat, and various vegetables. Cabbage (*Fictor* sp) was planted 1 May 1998 at a load of 15 000 plants/ha. The planting took place under wet-soil conditions in a field that previously had wheat. The plant spacing was 0.5 m, with three rows on one bed, 1.92 m wide. The cabbage was harvested toward the beginning of September.

Effluent quality and irrigation practices

The field was irrigated twice by sprinkling for germination, applying 50 mm. Total amount applied by drip irrigation, both SDI and conventional on-surface drip irrigation, was around 550 mm. Effluents were obtained from the adjacent effluent reservoir (Table 1). The nutrients in the effluent made artificial fertilization unnecessary.

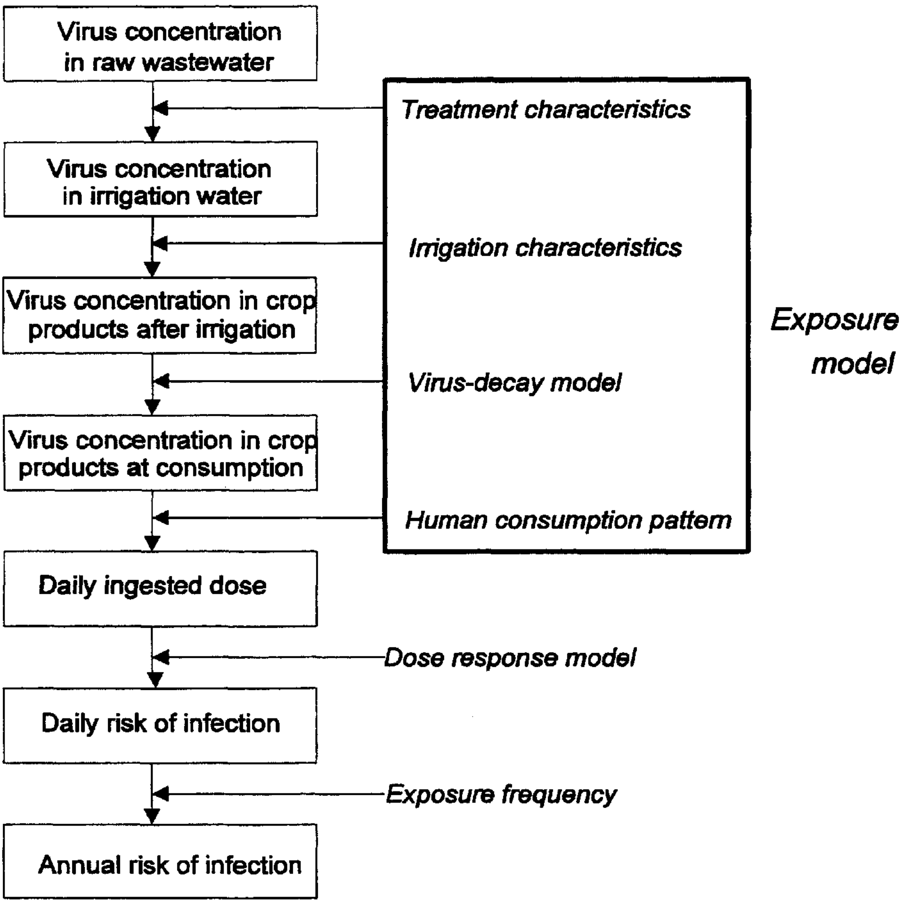

Figure 1. The procedure for determining the expected annual infection risk from consumption of effluent-irrigated agricultural products.

Risk-modeling

The risks associated with effluent reuse

Health-risk assessment is the process of combining toxicological and environmental data with information concerning the degree of exposure to external risks. The purpose of this is to determine the likelihood that a specific human population will have a particular adverse response (Paustenbach 1997). Quantitative microbial risk assessment has been used recently to estimate the risk of infection and illness from enteric pathogens in water and food. Several studies focus on health-risk assessment of wastewater reuse in agriculture (Asano and Sakaji 1990; Asano et al. 1992; Rose et al. 1996; Shuval et al. 1997; Tanaka et al. 1998).

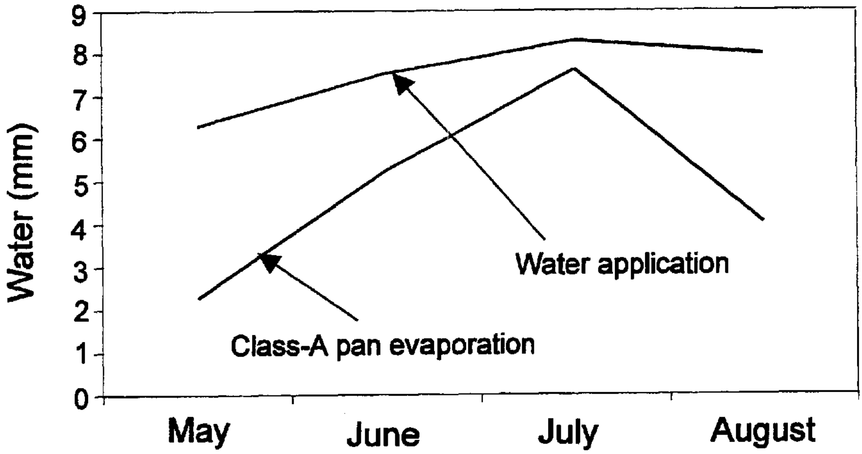

Figure 2. Class-A evaporation and effluent-application rate for cabbage irrigation, 1998.

Researchers have given little attention to exposure levels and related health-risk analysis for consumption of agricultural products irrigated using reclaimed wastewater. The exposure of consumers to contaminants from wastewater irrigation depends on several factors:

- Quality of the applied wastewater;
- Irrigation method;
- Time between the stages of irrigation, harvest, and subsequent product consumption; and
- Consumers' habits.

Previous works deal only roughly with the effect of the irrigation method, which is in practice one of the key issues in the estimation of exposure (Shuval et al. 1997; Tanaka et al. 1998). Some sources estimate an accidental ingestion of 100 ml water/year of irrigation, without specifying whether this concerns consumers or workers (Rose et al. 1996).

Table 1. Characteristics of the effluent applied in the cabbage irrigation, 1998.

		EC (dS/m)	TSS (mg/L)	BODt (mg/L)	BODf (mg/L)	NH_4 (mg/L)	SAR (–)
5 May	Raw	1.9	142	141	76	39.1	4.46
	Effluent	1.8	28	15	9	27.4	6.01
3 Jun	Raw	1.8	61	—	—	64.6	6.43
	Effluent	1.8	3.7	—	—	36.2	6.66
11 Jun	Raw	1.9	7.1	—	—	52.3	6.48
	Effluent	1.8	39	—	—	49.5	6.47
16 Jul	Raw	2.6	127	69	34	90.7	6.58
	Effluent	1.9	31	23	16	35.0	6.48
23 Jul	Raw	2.0	128	32	9	35.1	6.79
	Effluent	1.9	42	6.6	5.4	16.6	7.24
17 Aug	Raw	1.9	136	—	—	47.2	7.28
	Effluent	1.8	29	—	—	25.5	7.13
31 Aug	Raw	2.1	242	110	95	68.6	5.68
	Effluent	1.9	54	15	6.6	27.9	6.20

Source: Oron et al. (2001).
Note: —, not monitored; EC, electrical conductivity; SAR, sodium adsorption ratio; TSS, total suspended solids.

The present work focuses on the risk to consumers of using agricultural products irrigated with reclaimed domestic wastewater. Risks for farmers and workers are not in the scope of this work. The risks associated with microbial aerosol dispersion and the related impacts on adjacent living communities have been reported elsewhere (Applebaum et al. 1984; Ward et al. 1989).

The exposure-model features

Exposure is any of a series of events in which a person (or a community) comes into close contact with biological, chemical, or physical agents (Hammad and Manocha 1995). The prevailing mode of exposure to reclaimed wastewater for human consumers is ingestion. When modeling the exposure of a community to wastewater, researchers should consider the following:

- Wastewater-treatment characteristics;
- Route of virus migration from irrigation wastewater to and within the plant;
- Virus die-off during the period between last irrigation and agricultural raw-product consumption; and
- Consumption pattern of the population.

The route of exposure is commonly a human adult, who relies for dietary intake of fruits and vegetables entirely on effluent-irrigated crops. The corresponding assumptions are as follows:

- The study considers only exposure through ingestion;
- The virus concentration in raw sewage has a lognormal distribution (the arithmetic mean is 1000 colony-forming units [CFU]/L, and the standard deviation is 300 CFU/L [Rose et al. 1996; Tanaka et al. 1998]);
- The decay of pathogens during storage of effluent before irrigation is part of the treatment system;

- The total period between final irrigation and consumption equals the time between final irrigation and harvest plus the storage period, between harvest and consumption; and

- The study considers no cross-contamination of fruits and vegetables after harvesting.

Consumers eat an estimated 50% of their diet uncooked, unpeeled, and unwashed. A triangular distribution (minimum, 25%; maximum, 75%) is used to express the uncertainty of this estimate (Figure 3).

Data from previous literature and various field measurements provided the basis for ERM for assessing the risk of infection from consumption of agricultural products irrigated with wastewater. The ERM quantified the relationship between irrigation-wastewater quality and consumers' daily virus dose. The expected annual risk of infection was estimated stochastically with a numerical simulation, using the Monte Carlo simulation method and the ERM. Comparisons of the outcomes of the numerical computations included the given and obtained risks.

Numerical simulation of exposure scenarios are used to express the uncertainty and variability of the model's input parameters, characterizing them with a distribution pattern. Variability is the imprecision resulting from actual differences between segments of a population. Although the variability cannot be reduced, it provides additional data, thus increasing the accuracy of the analysis. Uncertainty stems from limitations on the thoroughness of measurement of a specific factor (Finley et al. 1994).

Examined scenarios

The nine initially examined scenarios combine treatment options (primary, secondary, and complete) and a specific irrigation technique (spray, drip, and SDI). The time between irrigation and harvest is assumed constant, at 15 days.

The study combined simulations of the initial nine scenarios with a range of exposure scenarios to analyze the influence of wastewater-treatment efficiency, irrigation method, and time between irrigation and agricultural-products consumption on human-health risk. Each scenario is a combination of wastewater-treatment efficiency (between 0 $\log_{10}$ and 6 $\log_{10}$), irrigation method, and the time between irrigation and consumption (between 0 and 30 days). The detailed input for the various scenarios is given in Table 2.

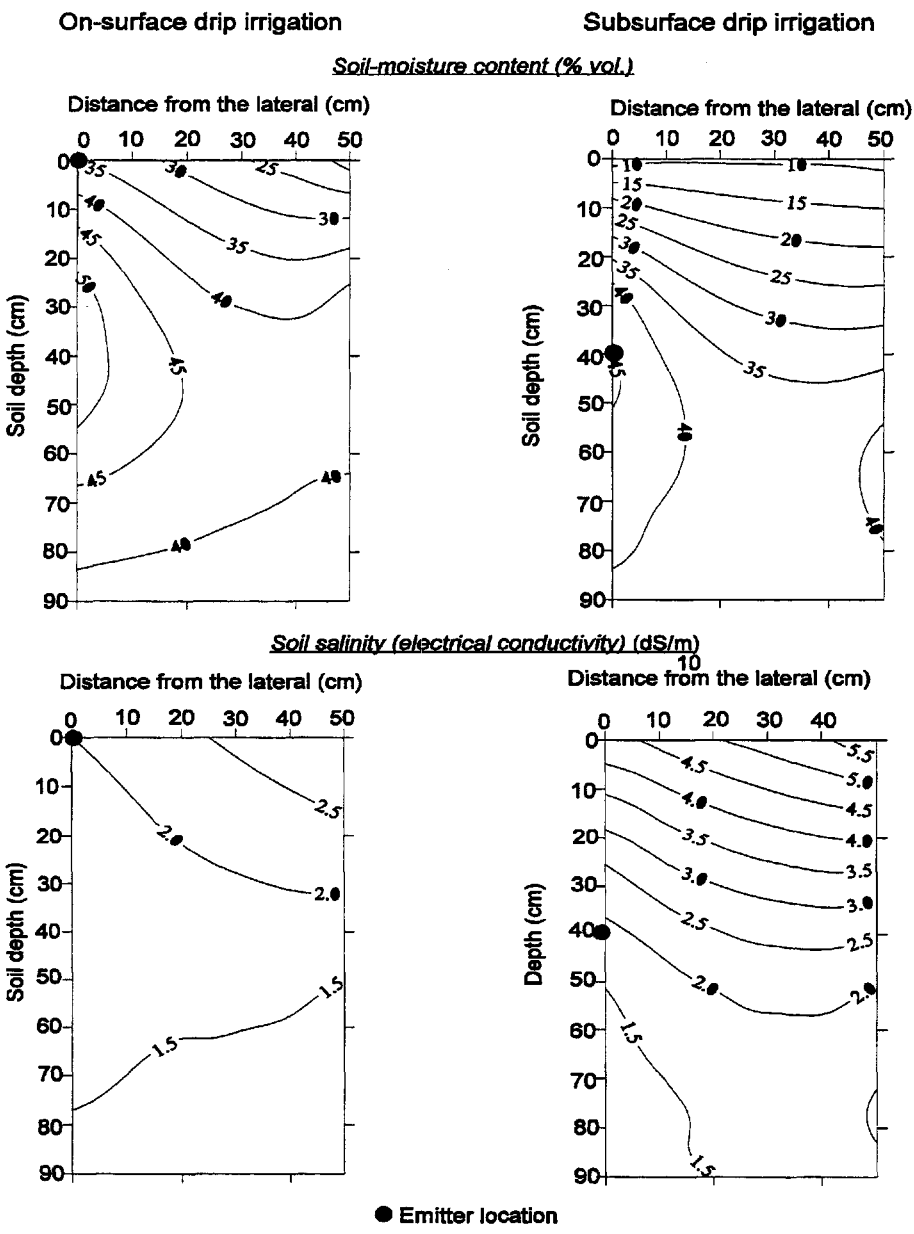

Figure 3. Soil-moisture and soil-salinity (electrical-conductivity) profiles in the cabbage field, 16 July 1998.

Table 2. Summary of input data for Monte Carlo simulation.

Data	Symbol	Unit	Mean value	Distribution
Virus concentration in raw sewage	C_0	CFU/L	1000	Lognormal; σ = 300
Kinetic decay constant	k	d^{-1}	0.69	—
Daily consumption of vegetables and fruits	M_i	g(kg × ca × d)	7.7	Step
Human body weight	M_{body}	kg	71	Normal
Percentage of vegetables and fruits consumed raw	f_{raw}	—	50	Triangular
Parameter β-Poisson model	α	—	0.247	—
Parameter β-Poisson model	β	—	0.232	—
Equivalent volume of spray irrigation	$V_{eq,si}$	L/g	1.6×10^{-4}	—
Equivalent volume of drip irrigation	$V_{eq,di}$	L/g	1.6×10^{-6}	Triangular
Equivalent volume of SDI	$V_{eq,sdi}$	L/g	1.6×10^{-7}	Triangular
Log_{10} wastewater treatment efficiency	E_r	log_{10}	Range: 0–6 log_{10}	
Period between irrigation and consumption	t_d	d	Range: 0–30 d	

Source: Oron et al. (2001).
Note: CFU, colony-forming units; SDI, subsurface drip irrigation.

The dose-response model

A dose-response model (DRM) was developed to examine the effect of consumption of effluent-irrigated agricultural products on human health. The DRM shows the relationship between the rate of exposure (virus dose) and the rate of effect on the consuming human community (response). Commonly, DRMs use animal behaviour or data obtained from controlled experiments in which healthy adults consume pathogens. Consequently, the data related to DRMs regarding human reaction are limited and provide the most uncertain models for health-risk analysis (McNab 1997; Paustenbach 1997).

The β-Poisson model (βPM) for rotaviruses is the dominant DRM. Rotaviruses are the type of enteric virus with the lowest infectious dose. The hypothesis of an independent action of single organisms forms the base for the βPM. The βPM was first used for drinking water and food technology and is an appropriate model to assess virus ingestion and the probability of infection (Rose and Gerba 1991; Rose et al. 1996; McNab 1997; Tanaka et al. 1998).

$$P_I = 1 - (1 - D_i / \beta)^{-\alpha} \qquad [1]$$

where P_I is daily probability of infection through ingestion of pathogens; D_i is daily consumed dose of contaminant (in CFU/days); β is the β-Poisson distribution coefficient; and α is a model parameter (α = 0.232 and α = 0.247; Haas 1983). Annual risk can be assessed successively from daily risk, as follows:

$$P_a = 1 - (1 - P_I)^{365} \qquad [2]$$

where P_a is the annual probability of infection through ingestion of pathogens.

Results

Field results

Irrigation

The field was irrigated three times per week, using data from class-A pan evaporation (Figure 2). Total amount applied under drip irrigation was about 5500 m^3/ha. Although the effluent had a fairly high content of suspended solids, this resulted in no emitter-clogging problems. Installing ring filters at the head of the irrigation distribution system prevented clogging problems, and injecting chlorine intermittently into the effluent transportation system enhanced the degradation of organic matter.

Soil moisture and salinity

The soil-moisture profile indicated that under drip irrigation, the water content close to the soil surface is higher than under SDI, which was around the emitter. The lowest soil salinity was detected near to the emitter, both for the drip irrigation and SDI systems. Therefore, SDI is advantageous for plants with a deep root system because of the high water content and low salinity near the emitter. However, for plants with a shallow root system, like cabbage, the increased salinity at the soil surface might be a problem, primarily for less tolerant plants (Figure 3).

Cabbage yield

The cabbage yield was measured on 31 August 1998 by harvesting the "heads" in two plots of 2 m × 2 m. The mean yield for DI was 55 500 kg/ha and only 45 800 kg/ha for SDI. The reason for the lower yield under SDI was probably due to the shallow root system, which was unable to use the water as efficiently as the plants under the conventional drip-irrigation system. Despite the importance of the yield, in this case the main objective was to examine the effect of the irrigation technology on soil and plant contamination. Further work is in progress toward obtaining higher and better quality yields.

Soil and plants contamination

Conventional and modified methods were used to analyze the microorganisms content in the wastewater, soil, and the plants (Doane and Anderson 1987; APHA 1995). Soil and plant contamination depends to a large extent on the effluent, soil conditions, and technology. The effluent had lower microorganisms content than that at other sites, probably because of extended detention in the open-surface reservoirs (Table 3). The main factors affecting survival of the microorganisms are the soil characteristics and actual moisture (Figures 4, 5, and 6). This finding holds for the fecal coliforms and the two types of coliphages. The coliphages are indicators of virus content in the soil.

Consequently, under SDI fruits were less contaminated than under drip irrigation. These findings actually strengthen the view that spray and sprinkler irrigation may lead to high levels of health and environmental risk.

Risk-modeling

Virus-removal efficiency of the wastewater-treatment system

The study examined several simulation scenarios for virus-removal efficiencies. Increasing virus-removal efficiency decreases the annual risk (upper confidence

Table 3. Pathogen content of effluent in cabbage irrigation, 1998.

Date	Fecal coliforms (per 100 mL)	Coliphage F+ (per 100 mL)	Coliphage CN-13 (per 100 mL)
3 June	26 000	600	6 200
11 June	46 000	250	950
3 July	44 000	4 200	7 400
16 July	35 000	6 200	2 400

Source: Oron et al. (2001).

limit [UCL]) of infection (Figure 6). With 15 days between irrigation and consumption, the virus-removal efficiency must be 4 $\log_{10}$ for sprinkler irrigation, 3 $\log_{10}$ for drip irrigation, and 2 $\log_{10}$ or less for SDI to comply with the United States Environmental Protection Agency (USEPA 1992) guideline ($<10^{-4}$).

Time between final irrigation and agricultural-product consumption

The study examined a range of scenarios of various periods between irrigation and consumption while keeping virus-removal efficiency in the wastewater-treatment system constant at 2 $\log_{10}$. By augmenting the time between the last irrigation and consumption it is possible to decrease UCL of the annual risk of infection (Figure 7). With a treatment efficiency of 2 $\log_{10}$ and the conditions set, 20 days must elapse for sprinkler irrigation, 13 days for drip irrigation, and about 11 days for SDI to comply with the USEPA guideline ($<10^{-4}$).

Combining virus-removal efficiencies and times between irrigation and consumption

The final modeling examined a broad range of combinations of virus-removal efficiencies in the treatment facilities and times between irrigation and consumption for the three main irrigation methods (Figure 8). The study ran one simulation for each combination of a virus-removal efficiency between 0 and 6 $\log_{10}$ (intervals of 1 $\log_{10}$) and an elapsed time between 0 and 30 days (intervals of 5 days). The results of the numerous simulations show the UCL of the annual risk of infection for sprinkler irrigation, drip irrigation, and SDI.

Summary and conclusions

The field experiments were conducted in a commercial cabbage field. The field had irrigation with secondary wastewater from a local stabilization pond, with temporary storage in an open-surface reservoir. In both experiments, the fields had

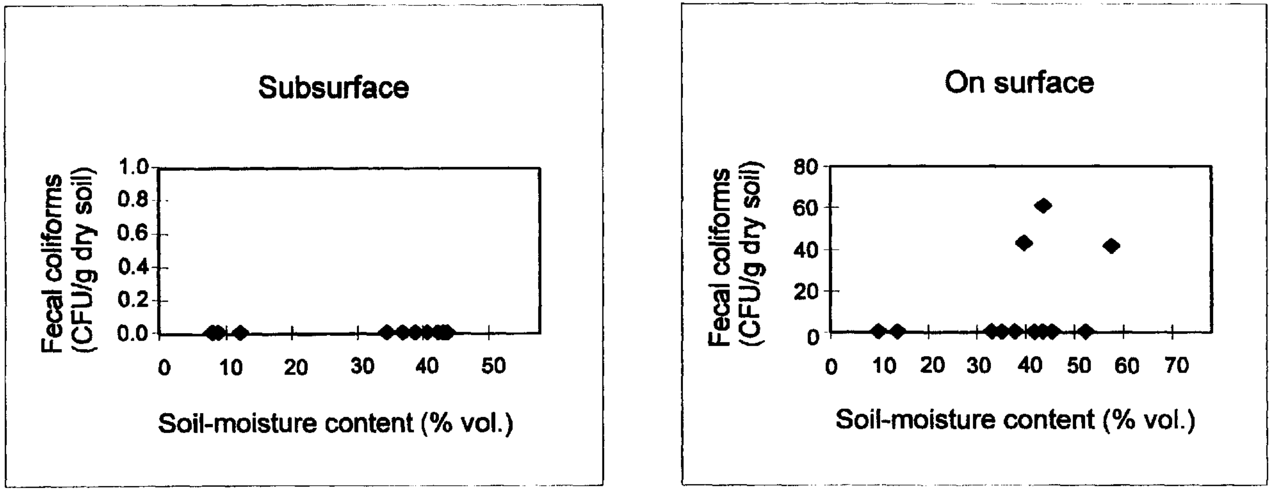

Figure 4. Fecal-coliform profiles in the soil after applying effluent for irrigation of cabbage, 16 July 1998. Note: CFU, colony-forming units.

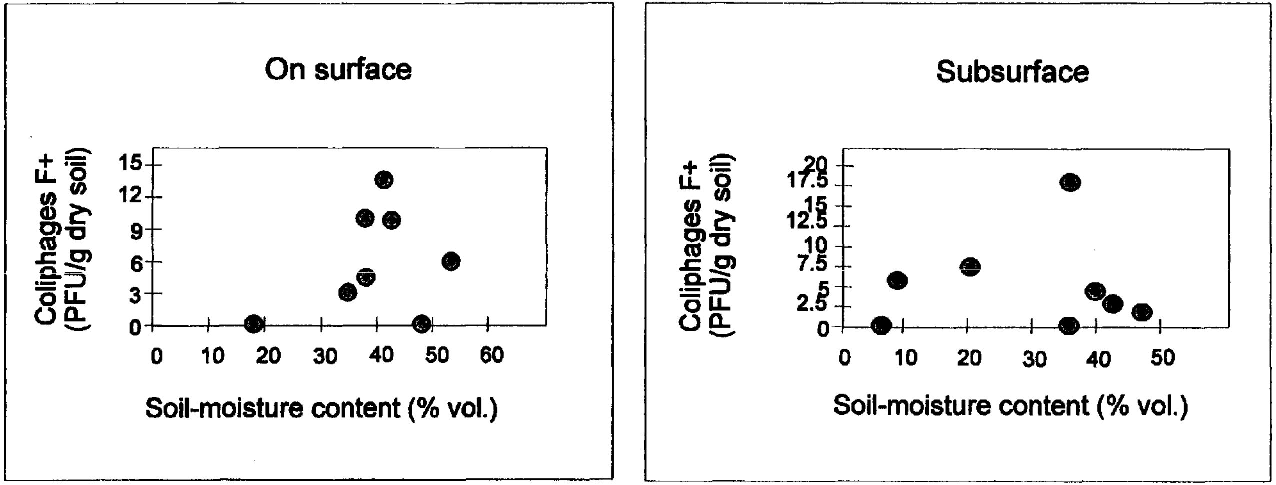

Figure 5. Coliphage-F+ profile in the soil after applying effluent for irrigation of cabbage, 16 July 1998. Note: PFU, plague-forming units.

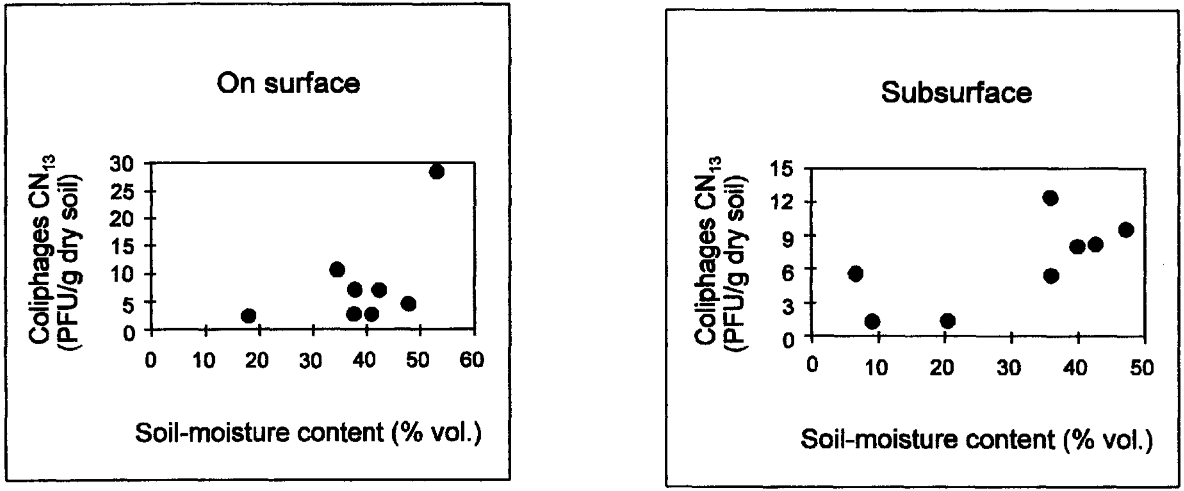

Figure 6. Coliphage CN-13 profiles in the soil after applying effluent for irrigation of cabbage, 16 July 1998. Note: PFU, plague-forming units.

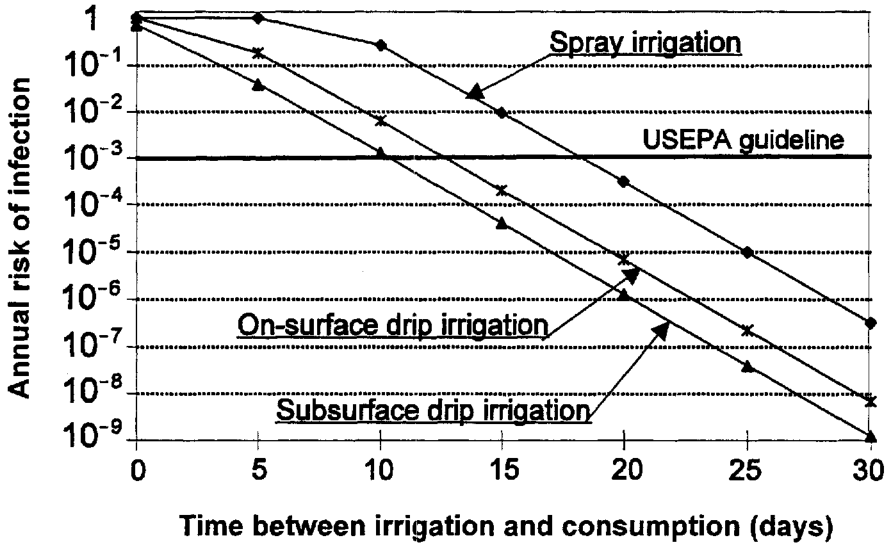

Figure 7. Relationship between annual risk of infection (upper confidence limit) and elapsed time between irrigation and agricultural-product consumption (based on 12 000 computer runs). The wastewater-treatment efficiency is constant at 2 $\log_{10}$. Note: USEPA, United States Environmental Protection Agency.

irrigation under on-surface and subsurface drip systems, applying tap water and effluent. Emitter depth was about 40 cm. Evaluation criteria included the yields, constituents in the soil, and contamination indicators, such as fecal coliforms and viruses in the soil and the plants.

It can be assumed for SDI that the soil medium establishes an excellent environment for a variety of complex processes of biodegradation (Taylor et al. 1978; Gerba et al. 1981; Dizer et al. 1984; Chase 1985; Powelson et al. 1990; Ho et al. 1991; Young et al. 1992; Farid et al. 1993; Guessab et al. 1993; Nasser et al. 1993). These processes induce the biodegradation of various microorganisms, which the soil particles then absorb (Taylor et al. 1978). Several complex and frequently interactive, physical, chemical, and microbiological processes restrain the transportation of the effluent and microorganisms through the porous media (Hickman et al. 1989). The efficiency of the microorganism adsorption, inactivation, and binding to the soil-surface particles depends on some characteristics of the porous media. Actually, these properties define the biofiltration efficiency and the potential for removal of microorganisms.

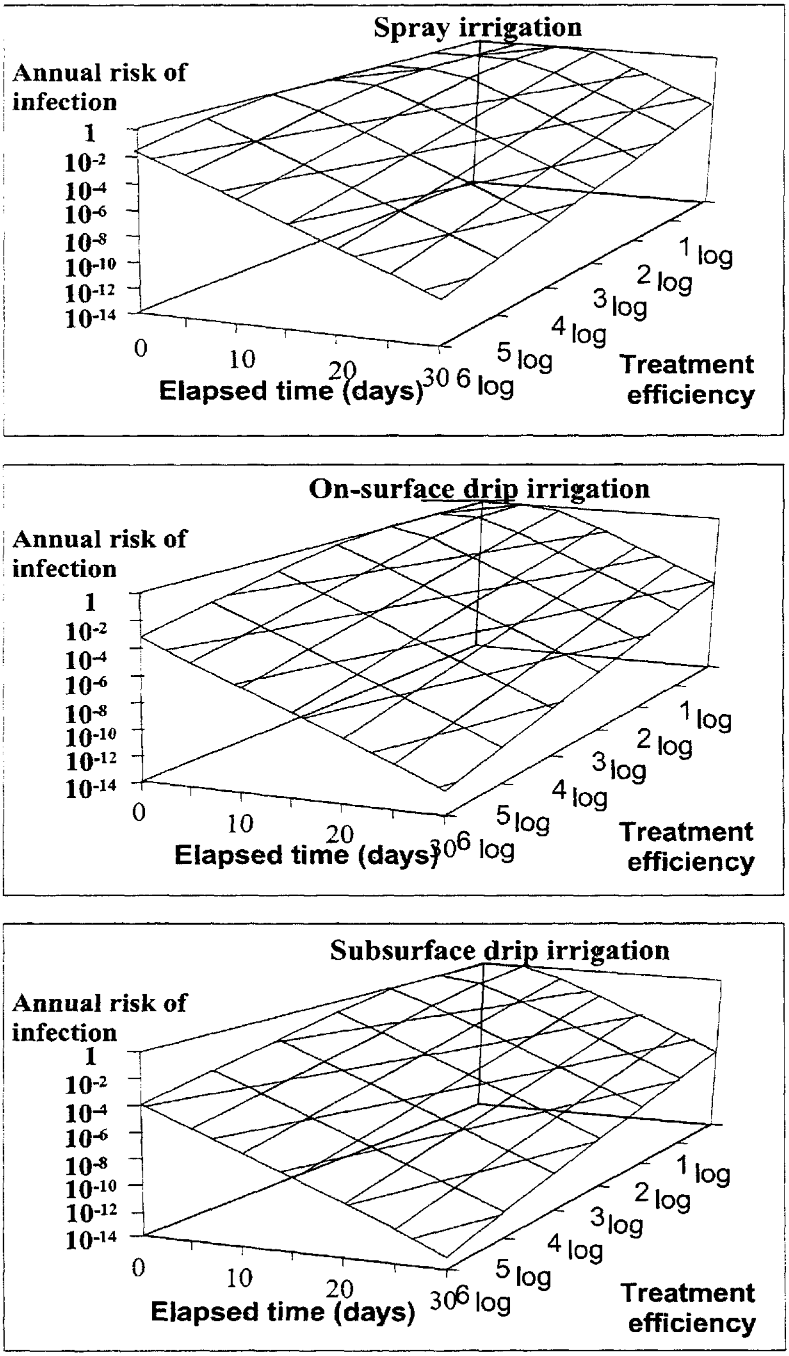

Figure 8. Relationship between annual risk, elapsed time between irrigation and consumption, and virus removal efficiency of the wastewater treatment system for three irrigation methods (based on 12 000 computer runs).

The experiments revealed no unexpected appearance or plant reaction. However, the plants developed less under SDI than under drip irrigation. The explanation for this could be the shallow root system of the cabbage plants and the depth of the SDI laterals (about 40 cm), which prevented adequate water supply.

The study developed a model for the assessment of risk of infection with wastewater irrigation of edible plants. The model takes into account several criteria:

- Quality of the wastewater;
- Irrigation method;
- Time between irrigation, harvest, and subsequent consumption; and
- Consumers' behaviour.

Risk assessment is a useful tool to upgrade reclamation schemes to acceptable health-safety standards. An increase in time between irrigation and consumption is the most effective operational change (one order of magnitude of risk for each 5 extra days). Other operational improvements are an increase in virus-removal efficiency of the wastewater treatment (one order of magnitude reduction of risk for each extra log of removal) and a switch from spray to drip irrigation, primarily SDI (two to three orders of magnitude reduction in risk).

A difference of 10 orders of magnitude occurs in the risk of infection between the various exposure scenarios with the same water quality. The large differences in risk of infection between exposure scenarios indicates the need to set risk-based criteria for wastewater reclamation, rather than a single water-quality guideline. Operational practices can limit exposure to pathogens and so play an important role in reducing risk.

The risk comparison in this study provided information on the relative risks. However, it did not provide a standard for acceptability of risk. To set acceptable-risk limits to ensure adequate protection of public health would be a much more complex task and would include socioeconomic considerations.

Acknowledgments

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Appendix 2

ACRONYMS AND ABBREVIATIONS

asl	above sea level
CFU	colony-forming units
EMU	Eastern Mediterranean University [northern Cyprus]
ERM	exposure-risk model
FAO	Food and Agriculture Organization of the United Nations
FEF	free-end furrows
GAP	Güneydoğu Anadolu Projesi (Southeastern Anatolia Development Project)
GDRS	General Directorate of Rural Services
IDRC	International Development Research Centre
MCSD	Mediterranean Commission on Sustainable Development
MOM	management, operation, and maintenance
NALR	National Authority for the Litani River
O&M	operation and maintenance
PAF	ponded alternative furrows
PCF	ponded continuous-flow furrows
ppm	parts per million

RDA	Regional Development Administration
SDI	subsurface drip irrigation
SHW	State Hydraulic Works
UCL	upper confidence limit
USEPA	United States Environmental Protection Agency
TRNC	Turkish Republic of Northern Cyprus
WUE	water-use efficiency

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