11 Improving Water Productivity in the Dry Areas of West Asia and North Africa

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Abstract

In the dry areas, water, not land, is the limiting factor in improving agricultural production. Maximizing water productivity, and not yield per unit of land, is therefore a better strategy for on-farm water management under such conditions.

This chapter highlights the major research findings at the International Center for Agricultural Research in the Dry Areas (ICARDA) regarding improving the water productivity of its mandate crops of wheat, barley, lentils, chickpea and faba bean. It is shown that substantial and sustainable improvements in water productivity can only be achieved through integrated farm-resources management. On-farm water-productive techniques, if coupled with improved irrigation-management options, better crop selection and appropriate cultural practices, improved genetic make-up and timely socio-economic interventions, will help to achieve this objective. Conventional water-management guidelines, designed to maximize yield per unit area, need to be revised for achieving maximum water productivity instead. A case study from Syria shows the applicability of this option. It illustrates that, when water is scarce, higher farm incomes may be obtained by maximizing water productivity than by maximizing land productivity.

Introduction

In the dry areas, agriculture accounts for about 80% of the total consumption of water. Water is rapidly becoming scarcer in west Asia and North Africa (WANA) and the competition for its use is growing more intense. In these areas, water is the factor that limits agricultural production. Most of the conventional sources of fresh water in the region have already been developed and the tendency to overexploit the natural resources is growing. Therefore, the only option left, in addition to developing some non-conventional sources, is to feed the ever-increasing population of the region using the same amount (or less) of water. Hence, the efficiency of water use in agriculture needs to increase in a sustainable manner, i.e. food production (quantitatively and qualitatively) per unit of water used has to be raised.

The International Center for Agricultural Research in the Dry Areas (ICARDA) aims to contribute to poverty alleviation in the dry areas by productivity improvement through sustainable natural-resources management. The ultimate goal is to improve the welfare of people in the dry areas of the developing world by increasing productivity and nutrition, while preserving and enhancing the natural-resources base of water, land and biodiversity. The challenge is to coordinate water and land management with the use of improved cultivars in viable cropping systems to increase water productivity (WP) and economic output. If agricultural production and livelihoods in the dry areas are to be sustained, even at current levels, greater priority must be given to improving WP and enhancing the efficiency of water use.

Options potentially available for coping with the consequences of water scarcity in agriculture in the dry areas include the development of additional sources of water and improving the management of all water uses.

Development of additional sources of water

Desalination

Desalination is gaining more importance as advances in the technologies are made. However, it is still an expensive process and hence is currently mainly used in areas where an affordable energy source is available, as in the oil-producing countries. Part of the desalinized water is used for irrigation. Breakthroughs in the cost of desalination would open up great opportunities for several countries of the region.

Marginal-quality water

Marginal-quality water offers good opportunities in many water-scarce areas. Potential sources include natural brackish water, agricultural drainage water and treated effluent. Research shows that substantial amounts of brackish water exist in dry areas, which can be either utilized directly in agriculture or desalinated at low cost for human and industrial consumption. Treated sewage effluent is an important source of water for agriculture in areas of extreme scarcity, such as Jordan and Tunisia. It is, however, a great environmental issue in other countries. The proper reuse of drainage water in agricultural production is also becoming attractive in many countries. By treating the marginal water as a resource rather than as a waste, it is possible to help the growers as well as to contribute to the alleviation of water scarcity and the sustainability of agricultural production systems.

Water transfers

Water transfers between water basins and across national borders have been extensively discussed in the region over the last two decades. Importation of water is under active consideration in the Middle East. The two most relevant options are to transport water by pipeline (Turkey's proposed peace pipeline) and by ship or barrage (big tanks or 'Medusa' bags). Both suggestions are subject to economic, political and environmental considerations, which are yet to be examined. Attempts to transfer water by balloons and tankers have been made but the cost is still high for agricultural purposes.

A project to transfer water by pipelines from Turkey to the Middle East countries was unsuccessful for economic and political reasons. Potential for such projects can only be realized with good regional cooperation and trust between the various parties.

Effective water management

Improved farm water management could have the greatest impact on water availability in dry areas. It is, however, a complex matter and also involves social, economic, organizational and policy issues, in addition to the technical ones. Research has demonstrated that proper management can more than double the return from water (Oweis, 1997). The major areas contributing to improved water management are discussed here.

Cost recovery of water

Although water is extremely valuable and essential in this region, it is generally supplied free or at low and highly subsidized cost. It is widely accepted that water pricing would improve efficiency and ensure better investment levels in water projects. However, the concept is seriously challenged in many countries of the region. The reasons are mostly sociopolitical and one cannot ignore these concerns as they are real and culturally determined. Innovative solutions are needed to put a real value on water for improving the efficiency of its use, while at the same time finding ways from within the local culture to protect the right of people to access water for their basic needs (El Beltagy, 2000).

Existing improved technologies

If properly applied, these technologies may at least double the amount of food produced from present water resources. Implementing precision irrigation, such as trickle and sprinkler systems, laser levelling and other techniques contribute to substantial improvement in water application and distribution efficiency. Although water lost during conveyance and on-farm application may not be a real loss from the basin perspective, its quality is likely to deteriorate and its recovery comes at a cost. To recapture and reuse water lost in this way is easier in large irrigation systems, but their construction comes at a high cost. There is a need to provide farmers with economic alternatives to current practices that are leading to wastage of water, and with incentives that can bring about the needed change.

Improved water productivity

Supplemental irrigation with a limited amount of water, if applied to rain-fed crops during critical stages, can result in substantial improvement in yield and WP. Application of water to satisfy less than the full water requirement of crops was found to increase WP and spare water for irrigating new lands. It has now been widely recognized that optimum WP is achieved by under-irrigating the crop. Adoption of this strategy requires an immediate adjustment to the conventional guidelines on irrigation in the region.

Optimizing agronomic practices and inputs, such as appropriate cropping patterns and fertilization, can also increase WP.

Using both Mendelian breeding techniques and modern genetic engineering, new crop varieties that can increase water-use efficiency while maintaining or even increasing yield levels can be developed. However, more work is needed to integrate all the above-mentioned approaches in practical packages to achieve the largest return from the limited water available.

Participation of all concerned in the management of scarce water resources is the key to successfully implementing more effective measures of water management. Players include the public and private sectors but, most importantly, representatives of the water users, particularly farmers and pastoralists, should be involved in the decision-making on water-management issues. Without appropriate policies, users cannot achieve the objectives of effective water management, but the inadequacy of current policies is the main constraint on improved water use in the region.

Water Scarcity and Mismanagement in the Dry Areas

The extent of the scarcity problem

The dry areas of WANA are characterized by low rainfall with limited renewable water resources. The average annual per capita renewable supplies of water in WANA countries are now below 1500 m^3, well below the world average of about 7000 m^3. This level has fallen from 3500 m^3 in 1960 and is expected to fall to less than 700 m^3 by the year 2025. In 1990, only eight of the 23 WANA countries had per capita water availability of more than 1000 m^3, the threshold for the water-poverty level. In fact, the 1000 m^3 level looks ample for countries like Jordan, where the annual per capita share has dropped to less than 200 m^3 (Margat and Vallae, 1999). Mining groundwater is now a common practice in the region, risking both water reserves and quality. In many countries, securing basic human water needs for domestic use is becoming an issue of concern, let alone the needs for agriculture, industry and the environment.

The current water supplies will not be sufficient for economic growth in all the countries of the region, except Turkey and Iran. Water scarcity has already hampered development in all countries of the Arabian Peninsula, Jordan, Palestine, Egypt, Tunisia and Morocco. Other countries of the region, such as Syria, Iraq, Algeria and Lebanon, are also increasingly affected as scarcity continues to get worse.

It is estimated that nearly one billion people live in the dry areas. About half of the workforce earns its living from agriculture, and water scarcity adds to their misery. At present, the average income of an estimated 690 million people is less than US$2.00 day^{-1}; the average income of 142 million of the 690 million is less than US$1.00 day^{-1} (Rodriguez and Thomas, 1999). Rural women and children suffer the most from poverty and its social and physical deprivations, which include malnutrition and high rates of infant mortality.

For most countries of WANA, almost half the crops of this dry region are grown under irrigation, and agriculture accounts for over 75% of the total consumption of water. With rapid industrialization, urbanization and population growth (double the world average), economic realities seem certain to reallocate water increasingly away from agriculture to other sectors. Moreover, opportunities for large captures of new water are few, if any. Most river systems suitable for large-scale irrigation have already been developed. It is becoming increasingly difficult to avoid unacceptable depletion of the flow to downstream users. Likewise, few major resources of renewable groundwater remain untapped. The tendency is now to overexploit existing sources, which, of course, is unsustainable.

The scarcity of water in some countries of the WANA region has reached the point where freshwater supplies are sufficient only for domestic and industrial use, which have priority. Very soon, the only water available for agriculture in these countries will be either saline or sewage effluent. This situation prevails already in the Gulf countries and will reach other countries, such as Jordan, in the next decade. Nevertheless, despite its scarcity, water continues to be misused. New technologies have made it possible for farmers to deplete aquifers to exhaustion. Desertification or land degradation is another challenge in the WANA region, closely related to water. Several international conferences and conventions, most recently the Convention to Combat Desertification, have brought these issues to the forefront of global concerns. Climatic variation and change, mainly as a result of human activities, are leading to depletion of the vegetative cover, loss of biophysical and economic productivity through exposure of the soil surface to wind erosion and shifting sands, water erosion, salinization of land and waterlogging. Although these are global problems, they are especially severe in the dry areas of WANA.

Compounding these problems is the expanding population. Population growth rates in WANA range up to 3.6%. The total population in WANA is expected to more than double, approaching 930 million by 2020. This will affect food supplies: the grain gap is projected to increase from 51 million t in 1995 to 109 million t by 2020 in the 23 countries of the region (Nordblom and Shomo, 1995). This is a conservative estimate that assumes no growth in per capita consumption. Assuming grain would continue to be priced at around US$130 t^{-1}, importing 109 million t of grain would cost US$14.2 billion!

It is projected that the vast majority of the 23 WANA countries will reach severe water poverty by the year 2025; ten of them are already below that level (Seckler *et al*., 1999). The increasing pressure on water resources will, unless seriously tackled, escalate conflicts and seriously damage an already fragile environment. This is particularly relevant in respect of countries with shared water resources. In WANA about one-third of the renewable water supplies are provided by rivers flowing from outside the region (Ahmad, 1996). Under the prevailing conditions, regionally integrated water-resources management is obviously the best way to manage the shared water at the basin level. However, considering the importance attached to national sovereignty and the fact that international laws on shared water resources are still inadequate, conflicts between several countries of the region will continue to occur.

The concept of water productivity

Seckler *et al.* (Chapter 3, this volume) have discussed the various concepts of water-use efficiency and/or WP as used in the literature on irrigated agriculture and, therefore, it is unnecessary to repeat them here. WP is shown in Fig. 11.1 in its dependence on crop yield (Y), transpiration (T), evaporation (E), evapotranspiration (ET) and irrigation water (I). From the diagram, transpiration WP (WP_T) and evapotranspiration WP (WP_{ET}) are defined as:

$$WP_T = Y/T$$
$$WP_{ET} = Y/(T + E)$$

It is evident that $WP_{ET} < WP_T$. However, if E = 0, then $WP_{ET} = WP_T$. In this chapter, reference to WP is to WP_{ET}. Furthermore, the irrigation water productivity, WP_I, is defined as follows:

$$WP_I = \Delta Y / \Delta ET$$

in which ΔY and ΔET are the increase in yield and evapotranspiration due to irrigation, respectively.

Integrated approach to on-farm water management

Newly developed water-resources management strategies have become more integrated in the sense of considering all aspects of water scarcity simultaneously. Current policies of water-resources management look at the whole set of technical, institutional, managerial, legal and operational activities required to plan, develop, operate and manage the water-resources system at all scales, i.e. farm, project, basin and national scale, while considering all sectors of the economy that depend on water. Sustainability is a major objective of these policies, wherein it is stipulated that the utilization of resources by future generations should in no way be limited by the use of current generations.

Fundamental to the successful integration of water-resources development and management is the involvement of all stakeholders to the greatest possible extent in the various management activities. Decisions regarding the best use of water must be made by evaluating the economic, social and environmental costs and benefits of alternatives. Integrated water-resources development also means looking at the impacts of policies on the social, economic and environmental aspects of the system.

Economic constraints are particularly important in developing sustainable water-management options. A sustainable-development path can only be secured if development policies consider economic

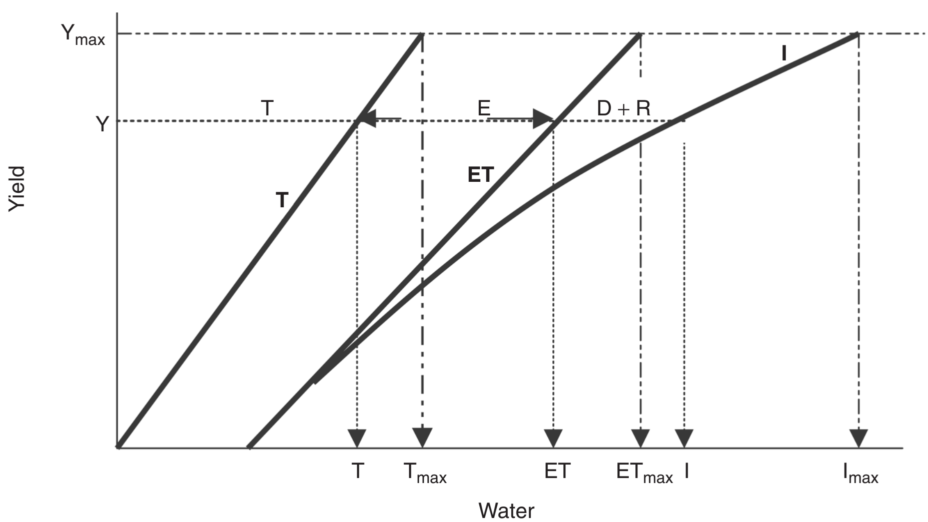

Fig. 11.1. A diagram for water-productivity terms and components: transpiration (T), evaporation (E), irrigation (I), evapotranspiration (ET), drainage (D) (deep percolation) and runoff (R).

aspects, such as costs and benefits to the society and individuals. This means that sustainable development and use of water resources should be compatible with the principles of sustainable economic activities. That is why many past irrigation schemes have failed or were much less successful than expected at the planning stage.

The strategy of any integrated approach for natural-resources management in the dry areas considers water as the central issue and water is accorded the highest priority. Utilization of soil and vegetation is closely linked to water and subject to climatic conditions. This strategy responds to the urgent need for improved productivity using less water by doing research on improved and sustainable WP at the farm level. Research in central and west Asia and North Africa (CWANA), which is the mandate dry region of ICARDA, focuses on the following five areas:

1. In rain-fed areas, optimizing supplemental irrigation, using the limited water available from renewable resources.
2. In drier environments (steppe), promoting efficient water harvesting for improved farmer income and environment.
3. In fully irrigated areas, developing on-farm packages for increased WP and soil and water quality.
4. In all the environments, developing strategies, methods and techniques for the safe and sustainable use of marginal water and treated sewage effluent in agriculture.
5. Developing strategies for the conservation and sustainable utilization of renewable groundwater resources.

Improving crop WP requires exploiting the genetic diversity of landraces and wild relatives for developing improved germplasm suited for stress-inducing environments. Germplasm improvement includes any of the following: increasing crop yield, disease resistance, heat and drought tolerance and, most importantly, the efficiency with which the crop uses water. The following two main strategies are pursued:

1. Selection for increased performance and WP by improving cultivars while maintaining current management conditions and water availability. This is done through improving crop cultivars adapted to marginal conditions through selection for performance, mainly yield and WP, directly in the target environment (Ceccarelli *et al.*, 1998). This is increasingly done through participatory plant breeding, involving farmers, to maximize the selection response. This strategy also focuses on the identification of morphological, physiological and agronomic criteria or traits that are related to increased performance under dry conditions. Such traits may then form the basis for indirect selection for yield and water productivity in dry environments. A new method involves employing marker-assisted selection for quantitative trait loci to identify breeding material with improved performance under dry conditions and higher water productivity.
2. Changing both management practices and crop cultivars concurrently. Different approaches in plant breeding and the numerous aspects of crop management are combined and integrated to develop viable strategies and sets of recommendations for productive, efficient and sustainable production systems. This combination of improved management practices and the crop plants or varieties themselves yields the greatest improvement in crop WP and can result in a quantum jump in both crop productivity and WP (Duivenbooden *et al.*, 1999).

To ensure generalization and transferability of the research results among dry regions, the concept of 'integrated research sites' was implemented together with work on agro-ecological characterization and modelling. A number of carefully selected integrated research sites was identified. Scientists from all disciplines work together on the most important issues in dry-area agriculture – that is, the need for more efficient, sustainable and water-efficient production systems. The strategies and technology packages developed and tested in these integrated research sites are then transferred or extended to other or larger areas, using bio-economic modelling to adapt them to the specific sites and situations with their specific biophysical and socio-economic conditions.

Major Research Achievements

Water-use-efficient techniques

In dry areas, moisture availability to the growing crops is the most significant single factor limiting production. Accordingly, this production factor must receive high priority. Technologies for improving yield, stabilizing production and providing conditions suitable for using higher technology are important, not only for improved yields but also for better WP.

Supplemental irrigation for rain-fed farming

The rain-fed areas play an important role in the production of food in many countries of the region and the world. They cover more than 80% of the land area used for cropping throughout the world and produce some 60% of the total production (Harris, 1991). In the Mediterranean-type climate, rainfall is characterized by its variability in both space and time. In general, rainfall amounts in this zone are lower than seasonal crop water requirements; moreover, its distribution is rarely in a pattern that satisfies the crop needs for water. Periods of severe moisture stress are very common and, in most of the locations, these coincide with the growth stages that are most sensitive to moisture stress. Soil-moisture shortages at some stages result in very low yields. Average wheat-grain yields in WANA range between 0.6 and 1.5 t ha^{-1}, depending on the amount and distribution of seasonal precipitation.

It was found, however, that yields and WP are greatly enhanced by the conjunctive use of rainfall and limited irrigation water. Research results from ICARDA and others, as well as harvests from farmers, showed substantial increases in crop yield in response to the application of relatively small amounts of supplemental irrigation (SI). This increase occurs in areas having low as well as high annual rainfall. Table 11.1 shows substantial increases in wheat-grain yields under low, average and high rainfall in northern Syria with application of limited amounts of SI. Applying 212, 150 and 75 mm of additional water to rain-fed crops increased yields by 350, 140 and 30% over that of rain-fed crops receiving an annual rainfall of 234, 316 and 504 mm, respectively. In addition to yield increases, SI also stabilized wheat production from one year to the next. The coefficient of variation was reduced from 100% to 20% in rain-fed fields that received SI.

The impact of SI is not only on yield but also, more importantly, on WP. The productivity of both irrigation water and rainwater is improved when they are used conjunctively. The average rainwater productivity of wheat grains in the dry areas is about 0.35 kg m^{-3}. However, it may increase to as much as 1.0 kg m^{-3} with improved management and favourable rainfall distribution. It was found that 1 m^3 of water applied as SI at the proper time might produce more than 2.0 kg of wheat grain over that using only rainfall. Data from a 5-year experiment (1991/92–1995/96) at ICARDA's research station in northern Syria (Table 11.2) show

Table 11.1. Yield and water productivity for wheat grains under rain-fed and supplemental irrigation (SI) in dry, average and wet seasons at Tel Hadya, northern Syria (from Oweis, 1997).

Season/annual rainfall (mm)	Rain-fed yield (t ha^{-1})	Rainfall WP (kg m^{-3})	Irrigation amount (mm)	Total yield (t ha^{-1})	Yield increase due to SI (t ha^{-1})	WP_I[a] (kg m^{-3})
Dry (234)	0.74	0.32	212	3.38	3.10	1.46
Average (316)	2.30	0.73	150	5.60	3.30	2.20
Wet (504)	5.00	0.99	75	6.44	1.44	1.92

[a]No surface runoff and drainage occur in the field.
WP_I, irrigation water productivity.

Table 11.2. Rainwater productivity (WP_R), combined rain- and irrigation-water productivity (WP_{R+I}) and irrigation-water productivity (WP_I) of bread-wheat grains in northern Syria.

Year	Rain (mm)	WP_R (kg m^{-3})	SI (mm)	WP_{R+I} (kg m^{-3})	WP_I (kg m^{-3})
1991/92	351	1.04	165	1.16	1.46
1992/93	287	0.70	203	1.23	2.12
1993/94	358	1.08	175	1.17	1.43
1994/95	318	1.09	238	1.08	1.06
1995/96	395	0.91	100	0.90	0.73
Mean water productivity		0.96		1.11	1.36

such an improvement in WP. The amount of water added by SI is not sufficient on its own to support any crop production. However, when supplementing rainfall by irrigation, the rainwater productivity (WP_R) increased in most of the years, particularly in the driest year (1992/93). On average, it increased from 0.96 to 1.11 kg m^{-3}. The last column in the table presents marginal irrigation WP (ratio of increase in yield to increase in evapotranspiration due to irrigation) with an average value of 1.36 kg m^{-3}.

The high WP of SI water is mainly attributed to alleviating moisture stress during the most sensitive stages of crop growth. Moisture stress during wheat flowering and grain filling usually causes a collapse in the crop seed filling and reduces the yields substantially. When SI water is applied before the occurrence of stresses, the plant may produce its potential yield.

Furthermore, using irrigation water conjunctively with rainwater was found to produce more wheat per unit of water than if used alone in fully irrigated areas where rainfall is negligible. In fully irrigated areas, wheat yield under improved management is about 6.0 t ha, using about 800 m^3 ha^{-1} of irrigation water. Thus, WP will be about 0.75 kg m^{-3}, one-third of that achieved with SI. This difference should encourage allocation of limited water resources to the more efficient practice (Oweis, 1997).

Unlike in full (or conventional) irrigation, the time of SI application cannot be determined in advance. When possible, and for rational allocation of limited water supplies, SI should be scheduled at the moisture-sensitive stages of plant growth. For example, for rain-fed cereals in the WANA region, the three most sensitive growth stages are seedling, anthesis and grain filling. Scheduling of SI should coincide with these sensitive periods to make certain that root-zone moisture does not limit growth.

Rainwater harvesting for the drier environments

The drier environments of WANA, the so-called *badia* or steppe, cover most of this region. The steppe receives inadequate annual rainfall for economic dry-farming production. The timing of precipitation in these areas is highly erratic. Most of this limited rainfall comes in sporadic, intense and unpredictable storms, usually on crusted soils with low infiltration rates, resulting in surface runoff and uncontrolled rill and gully water flow. Thus, the land is deprived of its share of rainfall and the growing crops endure severe moisture-stress periods, which significantly reduce yield, if any is produced. Therefore, a large part of the rainfall evaporates directly from the soil surface. Even some of the rain that infiltrates the soil to a shallow depth evaporates again. The rain that runs off usually joins streams and, if not intercepted, flows into a depression and loses its good quality and evaporates. The overall result is that the vast majority of precipitation water is lost as evaporation to the atmosphere without benefits; in other words, rainwater productivity is extremely low. Intervention in these areas is needed.

Water harvesting is one option for making rainwater more available to the crops in dry areas. It increases the amount of water per unit cropped area, reduces the severity of droughts and increases the productivity of rainwater.

Throughout history, water harvesting has shown good potential for increasing the efficiency of rainwater by concentrating it on a smaller area and thus ensuring enough moisture in the root zone of the plants. Indigenous systems, such as *jessour* and *meskat* in Tunisia, *tabia* in Libya, cisterns in north Egypt, *hafaer* in Jordan, Syria and Sudan and many other techniques, are still in use (Oweis *et al.*, 2001). Unfavourable socio-economic conditions over the last decades have caused a decline in the use of these systems, but recently increased water scarcity in the dry areas is favouring the revival of these systems.

Small basin microcatchments in the Muaqqar area of Jordan (mean annual rainfall of 125 mm) have supported almond-trees now for over 15 years without irrigation, despite several years of drought in which annual rainfall dropped below 60 mm. In the same area, small farm reservoirs were able to collect water every year with sufficient amounts to justify profitable agricultural development (Oweis and Taimeh, 1996). In the Mehasseh steppe of Syria (120 mm annual rainfall), rain-fed shrubs have a less than 10% survival rate, while those grown under microcatchments had an over 90% survival rate (Table 11.3). Shrub survival rate can be improved from 10 to 90% with the introduction of water-harvesting interventions (semicircular bunds), even during 3 drought years after 1 relatively normal year. In north-west Egypt (130 mm annual rainfall), small water-harvesting basins with 200 m^2 catchment support olive trees, and harvesting rainwater from the roofs of greenhouses provided about 50% of the water required by the vegetables grown within them (Oweis *et al.*, 2001).

These experiences and many others show that the productivity of rain in the drier environments can be substantially increased when a proper water-harvesting technique is implemented. In large-scale areas, methodologies for using remotely sensed data and ground information in a geographic information system (GIS) framework are often used to identify suitable areas and appropriate methods for water harvesting (Oweis *et al.*, 1998b). It was estimated that 30–50% of the rain in these environments might be utilized if water harvesting is practised, thus improving current rainwater productivity several-fold.

Successfully and sustainably integrating water-harvesting techniques within the agricultural systems in the dry areas is not an easy task. Several limitations exist, including socio-economic, technical and policy-related ones. Unclear landownership and lack of capacity of the farmers to implement these techniques are among the most important constraints.

Efficient on-farm water management

Optimum scheduling of irrigation is by far the most important means for improving crop WP and the key questions in irrigation scheduling are when to irrigate and how much water to apply.

Table 11.3. Shrub survival rate (%) in the Mehasseh steppe (120 mm annual rainfall), Syria, under semicircular microcatchment water harvesting with different sizes.

Year	Rainfall (mm)	Without water harvesting	Diameter of the semicircle (m) 2	4	6
1997/98	174	20	96	98	97
1998/99	36	7	92	95	93
1999/00	42	2	92	93	89
Mean		9.7	93.3	95.3	93.0

Deficit irrigation

Deficit irrigation is an optimizing strategy under which crops are deliberately allowed to sustain some degree of water deficit and yield reduction (English *et al.*, 1990). The adoption of deficit irrigation implies appropriate knowledge of crop water use and responses to water deficits, including the identification of critical crop growth periods and of the economic impacts of yield-reduction strategies. Figure 11.2 shows typical results on wheat, obtained from field trials conducted in a Mediterranean climate in northern Syria. The results show significant improvement in SI WP at lower application rates than at full irrigation. The highest WP of applied water was obtained at rates between one-third and two-thirds of full SI requirements, in addition to rainfall. The application of nitrogen improved WP, but, with deficit SI, lower nitrogen levels were needed (Fig. 11.2). This shows that, under deficit-irrigation practice, other cultural practices may also need to be adjusted. Planting dates, for example, interact significantly with the level of irrigation applied. Optimum levels of irrigation to maximize WP need to consider all these factors (Oweis *et al.*, 1998a).

WP is a good indicator for identifying the best irrigation-scheduling strategies with deficit SI of cereals (Zhang and Oweis, 1999), in analysing the water-saving performance of irrigation systems and management practices (Ayars *et al.*, 1999) and to compare different irrigation systems, including deficit irrigation. Experience from Syria showed that applying only 50% of the SI requirement to rain-fed wheat reduces full SI yield by less than 15% only (Oweis *et al.* 2000).

Strategies for optimal deficit SI in rain-fed areas require knowledge of rainfall amounts and distribution, in addition to the sensitivity to moisture stress during the various crop growth stages. Zhang and Oweis (1998) developed and used a quadratic wheat-production function to determine the levels of irrigation water for maximum yield and net profit. They also determined the yields for several levels of under-irrigation that would not reduce the farmer's income below that which the farmer would earn with full irrigation and limited water resources. For sustainable utilization of limited water resources and higher WP, the analysis indicates that a sound strategy would involve maximizing profit.

Analysis of 4 years' data (1996–2000) of SI with winter-sown food legumes on ICARDA's experimental fields, northern Syria, has shown similar trends in water-management options. Table 11.4 shows that, for chickpea, the optimal water management is to under-irrigate the crop by supplying one-third of its full water requirements. For lentil, deficit irrigation with two-thirds of its full water requirement seems to be the best choice. It can be seen that lentil and faba bean are more responsive to irrigation than chickpea.

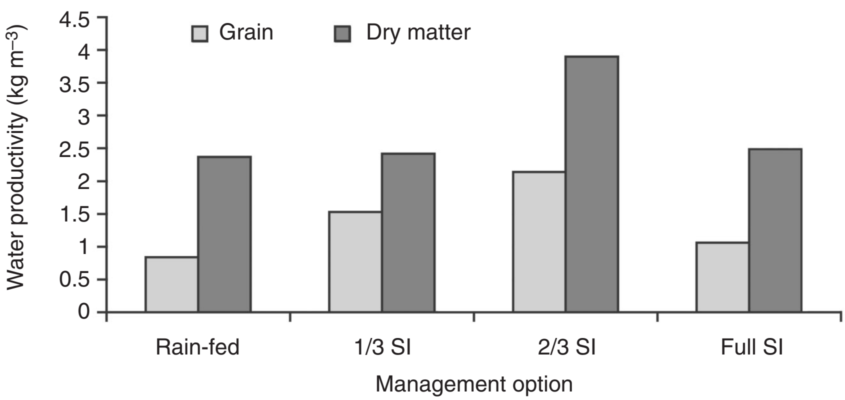

Fig. 11.2. Water productivity of wheat as affected by the amount of supplemental irrigation in northern Syria.

Table 11.4. Mean values of water productivity of four seasons (1996–2000) of lentil, faba bean and chickpea under rain-fed and supplemental irrigation at Tel Hadya, Aleppo, Syria.

Water-management option	Water productivity (production/water (kg m^{-3}))					
	Grain			Biomass		
	WP_R	WP_{R+I}	WP_I	WP_R	WP_{R+I}	WP_I
Lentil						
Rain-fed	0.57			2.14		
One-third SI		0.61	1.13		2.25	3.08
Two-thirds SI		0.69	1.34		2.44	3.56
Full SI		0.71	1.36		2.46	2.70
Chickpea						
Rain-fed	0.61			1.52		
One-third SI		0.68	1.23		1.77	2.70
Two-thirds SI		0.68	0.75		1.53	2.20
Full SI		0.55	0.34		1.48	1.60
Faba bean						
Rain-fed	0.51			1.40		
One-third SI		0.58	1.16		1.40	1.80
Two-thirds SI		0.62	1.53		1.53	2.40
Full SI		0.65	0.98		1.69	1.80

WP_R, rainwater productivity; WP_{R+I}, combined rain- and irrigation-water productivity; WP_I, irrigation-water productivity.

The decision on optimal strategies under varying conditions is a complex one, especially in rain-fed areas where year-to-year amount and distribution vary much. For example, it was found that sowing of rain-fed wheat spread out over the 3 months, November–January, substantially reduces the peak water demand during the critical SI period in the spring (Oweis and Hachum, 2001). This reduction is even greater when deficit irrigation is applied. The analysis was conducted using the simplified optimization model mentioned above. The results showed that a multisowing-date strategy reduced the peak farm water-demand rate by more than 20% thus potentially allowing a reduction in irrigation-system capacity and/or size. Also, the water demand of a larger area can be met with the same water supply. However, optimal sowing dates that minimize farm water demand do not always maximize total farm production and/or WP. The outcome depends on the crop water requirements and yield for each sowing date. Furthermore, selection of the optimal strategy is greatly influenced by the level of water scarcity.

The relationship between yield and water deficit has to be well known when planning deficit irrigation. The existing literature on this subject does not provide firm and ready-to-use information and, hence, there is a great need for research in this area. To determine when to irrigate and how much water to apply, suitable water-stress indicators should be used. These indicators may refer to the depletion of soil water, soil water potential and plant water potential or canopy temperature. For practical reasons, the most widely used indicators are soil water content and soil water potential. However, the spatial variability of the soil and irrigation depth gives rise to highly variable soil water content and/or potential data when these are obtained as point measurements.

There are different ways to manage deficit irrigation. The irrigator can reduce the irrigation depth, refilling only part of the root-zone soil-water capacity, or reduce the irrigation frequency by increasing the time interval between successive irrigations. In surface irrigation, wetting furrows alternately or placing them further apart is one way to implement deficit irrigation.

Cropping pattern and cultural practices

Among the management factors of the more productive farming systems are the use of suitable crop varieties, improved crop rotation, sowing dates, crop density, soil-fertility management, weed control, pests and diseases control, water-conservation measures, irrigation scheduling, water-quality monitoring and drainage. Integration of livestock into the farming system is important for nutrient cycling and fertilization of the soil. The challenge in WANA is to devise relevant practical solutions to the very low yield and WP in the region and implement them in the context of both local biophysical and socioeconomic constraints.

The identification of appropriate crops and cultivars with optimum physiology, morphology and phenology to suit local environmental conditions is one of the important areas of research within cropping-system management for improved WP. Plant breeders aim at well-adapted cultivars with higher yield potential, tailored to the specific agroclimatic conditions. The breeding programme seeks improvement of crops so that they are tolerant to cold, drought and heat and resistant to diseases and insects and have vigorous early growth to reduce evaporation losses from the soil surface (Zhang *et al.*, 1998). A seasonal shifting, i.e. development of crop varieties that can be grown or sown in winter (instead of spring) under a lower evaporative demand, represents an additional challenge for breeders aiming at using scarce water more efficiently. However, traits such as winter-hardiness and disease resistance of the cultivars have to be improved. The development of crop varieties for early-growth vigour has been a major concern of ICARDA's winter-cereal breeders for many years.

In the winter-rainfall environment of the WANA region, despite temperature limitations on growth, it pays to sow early (late autumn) so that as much as possible of the crop's growth cycle is completed within the cool, rainy winter and early spring period. Delaying the sowing date prevents crop germination and the establishment of seedlings, because of the rapid drop in air temperature starting generally in November. In the lowlands of the Mediterranean region, where continuous cropping of pure cereal or cereal–legume rotations prevail, mid-November was found to be the optimum sowing time for cereals. Every week's delay after this time results in a yield decrease of 200–250 kg ha^{-1}. If the onset of seasonal rain is delayed, early sowing can be realized by SI.

Soil fertility is another critical factor in WP in WANA's agriculture. Water plays a significant role in fertilizer-use efficiency. Improved fertility improves WP and can therefore stabilize production and enable crops to exploit favourable rainfall in good years. Given the inherent low fertility of many dry-area soils, judicious use of fertilizer is particularly important. Under rain-fed conditions, the application rate of N fertilizer is not high. In northern Syria, 50 kg N ha^{-1} is sufficient under rain-fed conditions. However, with water applied by SI, the crop responds to nitrogen up to 100 kg N ha^{-1}, after which no benefit is obtained. This rate of N greatly improves WP. It is also important that there is adequate available phosphorus in the soil so that the response to N and applied irrigation is not constrained (Ryan, 2000). Cereal–fallow and continuous cereal cropping are the predominant crop rotations in WANA. The poor productivity and deterioration of the natural-resources base of such cropping systems are obvious. Including legumes (for human food and/or animal feed) in the rotation has proved to be beneficial for sustainable crop production. The major beneficial effect of legumes is generally attributed to their addition of fixed N to cropping systems. However, other effects, such as increased cereal yield, improved WP and soil conditions and interruption of disease and pest cycles, are also important.

Among the major soil factors affecting WP are depth, texture, structure and crusting, salinity and fertility. Tillage (form, depth, frequency and timing) and soil-surface management play important roles in enhancing WP, particularly in dry areas. Calcareous soils, formed from limestone residuum, predominate in the WANA region, with variable textures, depths and slopes. Organic-matter content is generally low.

Most documented research on WP is on single crops, in which the performance of each crop is studied separately. To obtain the optimum output of crop production per unit input of water, the monocrop WP should be extended to a multicrop WP in which more than one crop is sharing the use of the unit of input. WP of a multicrop system is usually expressed in economic terms, such as profit or revenue. While economic considerations are important, they are not adequate as indicators of sustainability, environmental degradation and natural-resources conservation. What may appear to be economically viable in the short run may be disastrous in the long run.

Good soil- and crop-management practices can considerably increase the efficiency with which water available from precipitation and irrigation can be used. Improved WP can be achieved if the crops are well established and adequately fertilized, weeds are controlled and appropriate crop rotations are used (Pala and Studer, 1999). These activities should also be considered together with the proper management of the soil if productivity is to be sustained and resources are to be conserved in the long term. As mentioned before, soils of the WANA region are predominantly calcareous, frequently deficient in phosphates, with variable depths and textures governing the maximum amount of water that can be stored and, hence, the effective length of the growing seasons. Maximizing the use of water available for crop growth is mainly done through increasing the water supply to crops, increasing their transpiration and decreasing evaporation from the soil surface (Gregory, 1991). The suggested technology packages vary with agroecological conditions and farmers' objectives.

Many dry-area soils are inherently low in fertility, as was pointed out before, and the correct application of fertilizers is therefore essential. Extensive work in Syria (Pala *et al.*, 1996) demonstrated the benefits of appropriate fertilization for WP and therefore for production and yield stability, especially of wheat and barley, in WANA. In deficient soils, seedbed phosphate (usually together with a small dose of nitrogen) enhances the rate of leaf expansion, tailoring, root growth and phenological development, ensuring faster ground cover and canopy closure, and earlier completion of the growth cycle before rising temperatures increase the atmospheric demand (Gregory, 1991).

An example of the interaction between fertilizer application and WP is presented in Fig. 11.3 (Oweis, 1997). The data show that an additional 50 kg N ha^{-1} may double the WP of SI. However, the optimum level of N is site-specific and dependent on the irrigation depth.

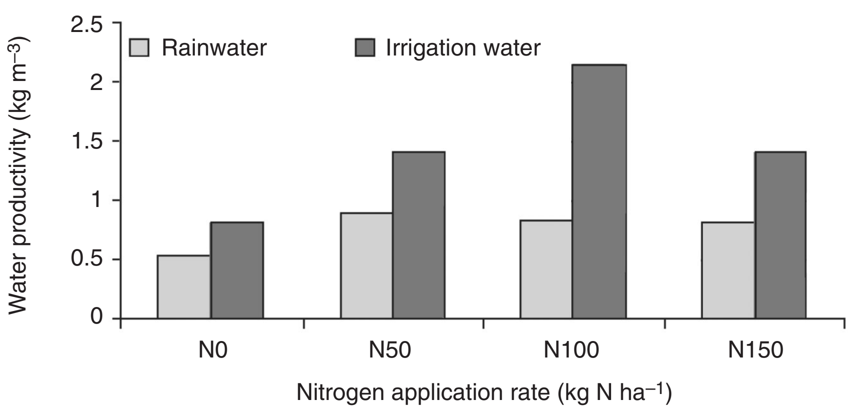

Fig. 11.3. Water productivity of wheat as affected by the rate of nitrogen application under rain-fed and supplemental irrigation in northern Syria (from Oweis, 1997).

More efficient crop varieties

Among ICARDA's research outputs are technologies designed to increase productivity while conserving and enhancing the natural-resources base. Germplasm-improvement programmes focused on increasing the productivity of barley, durum and bread wheat and food and forage legumes, along with integrated pest management in cereal- and legume-based cropping system. ICARDA-improved varieties cover about 90% of spring bread wheat in WANA, with a remarkable increase in yield for the benefit of resource-poor farm households. This programme operates in close partnership with national agricultural research systems (NARS) and other sister centres and advanced research institutions. The application of decentralized breeding and farmer participatory methods has increased the efficiency of variety development by enabling researchers to work directly with farmers in assessing varieties for specific adaptation.

Exploitation of the interaction of genotype and management

The identification of crops and cultivars with the optimum physiology, morphology and phenology for local environmental conditions and especially for the pattern of water availability is an important area of research. For example, the selection for improved response to irrigation has been conducted in lentil and chickpea (Hamdi *et al.*, 1992). Breeding and selection for improved WP and the use of genotypes best adapted to specific conditions can improve soil water use and increase WP (Studer and Erskine, 1999).

As was mentioned before, combining more appropriate cultivars with improved management practices results in major improvements in crop yield and WP. The following two case histories illustrate this simultaneous change in both genotype and management, with the first involving early sowing in the food legume chickpea and the second describing the use of SI in wheat production.

Early sowing of chickpea

In the Mediterranean region, rain falls predominantly in the cool winter months of November to March. Traditionally, chickpea is sown in late February and early March. From March onwards, the crop experiences increasingly strong radiation and a rapid rise in temperature, which cause an increase in the rate of leaf-area development, with consequent high evapotranspiration. This period of high evaporative demand occurs at the end of the rainfall period, when the residual soil moisture is inadequate to meet the evaporative demand. Therefore, the crop experiences drought stress during the late vegetative growth and reproductive growth and produces a low yield. Changing from the traditional spring sowing to winter sowing is possible but only with cultivars possessing cold tolerance and resistance to key fungal diseases (Singh *et al.*, 1997; Studer and Erskine, 1999).

The average gains in seed yield from early-sowing chickpea over three sites and ten seasons is 70% or 690 kg ha^{-1}, which translates into an increase in WP of 70% (Fig. 11.4; Erskine and Malhotra, 1997). In 30 on-farm trials comparing winter with spring chickpea in northern Syria, the mean benefit of winter sowing in seed yield and WP was 31% (Pala and Mazid, 1992). Currently, an estimated 150,000 ha of chickpea is winter-sown in the WANA region (Singh and Saxena, 1996).

Improved wheat cultivars under supplemental irrigation

The use of SI is another example of a concurrent change in both management practice and water-responsive cultivars to increase WP. This example demonstrates the need to combine changes in management with the use of adapted varieties in SI of wheat. SI requires varieties that are adapted to or suitable for varying amounts of water application. Appropriate varieties need first to manifest a strong response to limited water applications, which means that they should have a relatively high

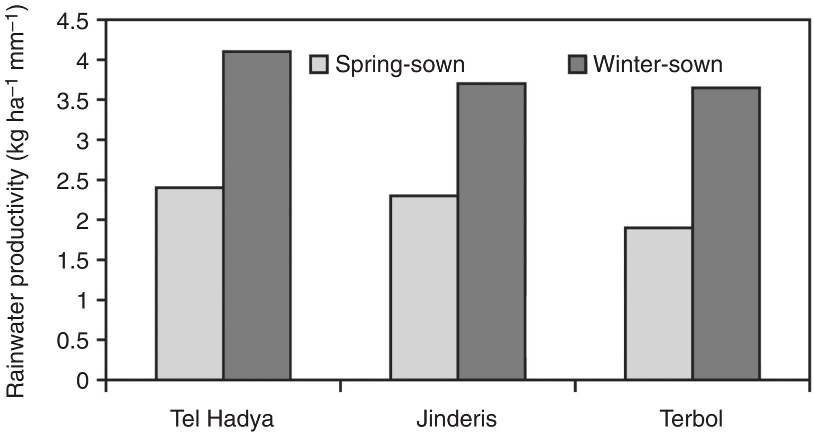

Fig. 11.4. Rainwater productivity of winter- and spring-sown chickpea grains in north Syria (from Erskine and Malhotra, 1997).

yield potential. At the same time, they should maintain some degree of drought resistance and hence express a good plasticity. In addition, the varieties should respond to the higher fertilization rates that are generally required under SI (Oweis, 1997; Oweis *et al.*, 1999) and should resist lodging, which can occur in traditional varieties under irrigation and fertilization. Figure 11.5 shows the variations in the response of two durum- and two breadwheat varieties to various water-management options.

Water productivity versus land productivity

The case of wheat

In WANA, where water is more limiting than land, the objective of irrigated agriculture should be to maximize the return per unit of water and not per unit of land. This should yield higher overall production, since the saved water can be used to irrigate new land with higher production. Higher WP is linked with higher yields. This parallel increase in yields and WP, however, does not continue all the way. At some high level of yield (pro-

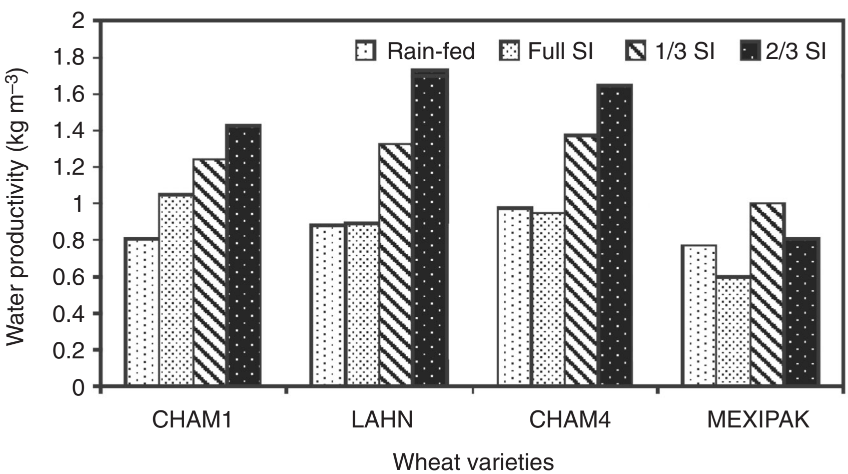

Fig. 11.5. Four-year averages of rain and supplemental irrigation water productivity for wheat varieties grown in northern Syria (from T. Oweis 2001, unpublished data). CHAM1 and LAHN are durum.

duction per unit of land), incremental yield increase requires higher amounts of water. This means that WP starts to decline as yield per unit land increases above certain levels. Figure 11.6 shows the relation between yield increase and WP increase for durum wheat under SI in Syria.

It is clear that the amount of water required to produce the same amount of wheat at yield levels beyond 5 t ha^{-1} is much higher than the water requirement at lower levels. It would be more economical to produce only 5 t ha^{-1} and then use the saved water to irrigate new land than to produce maximum yield with excessive amounts of water at low WP. This, of course, applies only when water, and not land, is limiting and without sufficient water to irrigate all the available land. When the curvilinear relationship of Fig. 11.6 applies, which is not always the case, maximum WP occurs at less than the maximum yield level per unit area.

The association of high WP values with high yields has important implications for crop management for achieving efficient use of water resources in water-scarce areas (Oweis *et al.*, 1998a). For example, attaining higher yields with increased WP is only economical when the increased gains in crop yield are not offset by increased costs of other inputs. The curvilinear WP–yield relationship makes clear the importance of attaining relatively high yields for efficient use of water. Policies for maximizing yield and/or net profit should be considered carefully before they are applied under water-scarce conditions. For example, guidelines for recommending irrigation schedules under normal water availability (Allen *et al.*, 1998) may need to be revised when applied in water-scarce areas.

The Syrian case-study

As earlier reported, research has shown that applying only 50% of full SI requirements (over that of rainfall) causes a yield reduction of only 10–15%. This finding, in light of the increasing water scarcity in Syria, encouraged ICARDA and the Extension Department of the Ministry of Agriculture to further test deficit SI strategies at farmers' fields. The hypothesis was that applying 50% of SI requirements to the whole field, while maximizing WP, will be more beneficial to the farmer than applying 100% of wheat irrigation requirements to half of the field, while

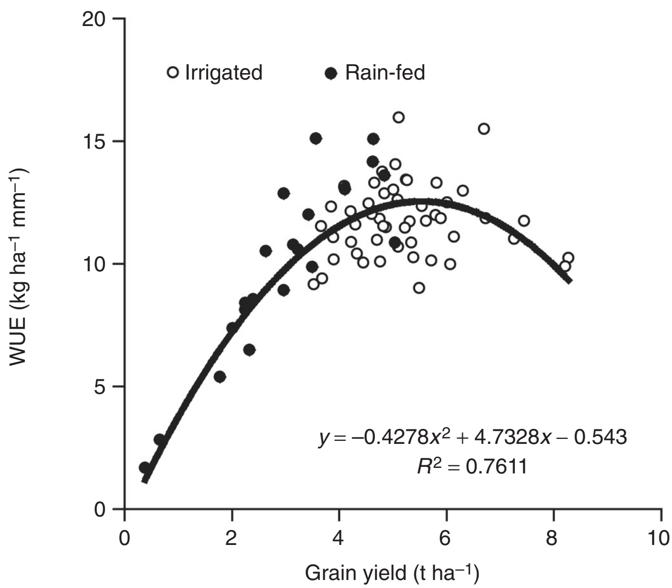

Fig. 11.6. Relationship between crop water productivity and crop grain yield for durum wheat under supplemental irrigation in Syria (from Zhang and Oweis, 1999). WUE, water-use efficiency.

leaving the other half rain-fed. The demonstrations were conducted on farmers' fields and managed collectively by the farmers, the researchers and the extension officials.

The farmer-managed demonstration plots were established over 6 years in the rain-fed areas with annual rainfall ranging from 250 to 450 mm. Rain-fed wheat yields in this area are generally low (less than 2 t ha^{-1}) and variable from one year to the next. Supplemental irrigation is practised in the area and has shown good potential to increase and stabilize production. However, it was observed that farmers tended to over-irrigate and the groundwater in the region had been continuously depleted.

Each farmer's land was divided into four 1 ha parts: the first was left rain-fed, the second was irrigated in the usual manner by the farmer, but water amounts were measured, the third part was irrigated such that no moisture stress occurred and the fourth part was irrigated with 50% of the full irrigation requirements. Water requirements were determined using evaporation from class A pans installed in the field, using appropriate pan and crop coefficients. Rain was also measured at the farm. Irrigation water was given from wells or public canals and measured by calibrating the flow rate and determining the time needed to apply the required amount. At the end of the season, the crop yields were measured and other data were collected. The farmers used improved wheat cultivars and recommended inputs and cultural practices at each site.

When there is not enough water to provide full irrigation for the whole farm, the farmer has two options: to irrigate part of the farm with full irrigation, leaving the other part rain-fed, or to apply deficit SI to the whole farm. Assuming that, under a limited water resource, only 50% of the full irrigation required by the farm would be available, the option of deficit irrigation was compared with other options. The results are summarized in Table 11.5. They show that, under the rainfall conditions prevailing in Syria during the years 1994–2000, a farmer with a 4 ha farm would, on average, produce 33% more grain from his/her farm if he/she adopted deficit irrigation than if full irrigation was applied. The advantage of applying deficit irrigation increased the benefit by over 50% compared with that of the farmer's usual practice of over-irrigation. Thus, the application of deficit SI, when water resources are limited, could potentially double the land area under irrigation. The results of this programme point to the possibility of producing more food with less water.

Present Needs and Future Directions

In rain-fed areas, water-conservation measures are of primary importance. As discussed above, they include such practices as fallow management, control of runoff and water harvesting. Integrated with these practices are the selection or development of

Table 11.5. Wheat-grain production scenarios for 4 ha farms with various strategies of supplemental irrigation in Syria.

Management strategy	Rain-fed (342 mm)	Farmer's practice	Full SI	Deficit SI
Total water applied (m^3)		2980	2220	1110
Grain yield (t ha^{-1})	1.8	4.18	4.46	4.15
Water productivity (kg m^{-3})	0.53	0.70	1.06	1.85
Possible 4 ha farm production (t) if water is not limiting	7.2	16.7	17.8	16.6
Possible 4-ha farm production (t) under limited water (50% of full irrigation requirement is assumed to be available)	7.2	10.8	12.5	16.6

high-yielding, drought-tolerant crop varieties, efficient use of fertilizers, combating pests and diseases, crop rotation and optimal planting dates to maximize the probability of rainfall use during critical periods of crop growth. The collective effects of such practices are complex when integrated with rain-fed farming systems and yet they are even more pronounced under irrigated agriculture.

Until recently, large irrigation projects have been given high priority, while small-scale water development for agriculture has received inadequate attention. It becomes evident now that small-scale irrigation, including SI for rain-fed agriculture, and a variety of water-harvesting techniques have considerable potential to meet agricultural and domestic water needs and to improve WP. Small-scale water-development programmes can fulfil many local water needs and have considerable global potential for the achievement of sustainable agricultural development. In a small-scale water-development scheme, individual farmers or communities develop and operate most project activities. However, technical assistance is often necessary during survey, design, construction and maintenance. Such undertakings can often contribute to both development and conservation, while enhancing local involvement in environmental management, promoting equity, improving the standard of living and thus helping to slow or prevent migration to urban areas.

Modern irrigation technologies in developed countries are very sophisticated and expensive. They are automated and computerized, equipped with such components as sensing devices, pressure regulators, filters and sensors. All this is helpful because it saves labour, which is usually expensive in industrial countries, but irrigation technologies do not need to be so complicated and expensive in developing countries. It is possible to simplify these technologies and adapt them to the needs of the resource-poor farmers of developing countries. Irrigation can be made a small-scale operation for poor farmers or communities, who have a need for the most efficient irrigation system to produce enough food for themselves and others.

The problem is how to use water more efficiently, while preventing environmental damage, in order to get a better return for the cost involved in making water available and in applying it. Applying too much water to the land causes a host of adverse effects, such as salinity build-up if drainage is poor, decline in crop yield due to aeration problems and loss of nutrients and energy and water wastage. We should remember that salinization was a major factor in the failure of past civilizations in many parts of the world.

Major Research Issues in Water-scarce Areas

There is no doubt that improving the productivity of water in dry areas will continue to be a priority. Efforts to direct new research and the transfer of available technologies to overcome water shortages are very much needed. Coordination of these efforts within an agreed-upon framework may enhance their impact. Elements of the research and technology framework would include:

1. The development of alternative land-use systems and cropping patterns for improved water use that are economically competitive and that respond to changing markets and demands in various agroecologies and socio-economic situations.
2. The development and transfer of alternative irrigation technologies with high water productivity and suitable for irrigation in these alternative land-use systems.
3. Developing new guidelines for irrigation scheduling under water-scarce conditions. Conventional guidelines are suitable only under normal water supply.
4. Developing methodologies for the assessment of water use at basin level of representative areas for evaluating the amounts of depleted and recoverable water and the economic returns.
5. Improving crop materials (germplasm) for higher WP in addition to the conventional target of high yield.
6. Evaluating the environmental consequences of conservative management of scarce water and ways to mitigate adverse effects.

7. Maintaining a balance between water allocation for food and for the environment under dry conditions.

8. Providing socio-economic incentives for improved water management at the farm level and development of appropriate policies.

References

Ahmad, M. (1996) Sustainable water policies in the Arab region. Paper presented at the Symposium 'Water and Arab Gulf development: problems and policies', University of Exeter, UK.

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998) *Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements*. FAO Irrigation Drainage Paper 56, FAO, Rome, 300 pp.

Ayars, J.E., Phene, C.J., Hutmacher, R.B., Davis, K.R., Schoneman, R.A., Vail, S.S. and Mead, R.M. (1999) Subsurface drip irrigation of row crops: a review of 15 years' research at the Water Management Research Laboratory. *Agricultural Water Management* 42, 1–27.

Ceccarelli, S. and Grando, S. (1991) Environment of selection and type of germplasm in barley breeding for low-yielding conditions. *Euphytica* 57, 207–219.

Ceccarelli S., Grando, S. and Impiglia, A. (1998) Choice of selection strategy in breeding barley for stress environments. *Euphytica* 103, 307–318.

Duivenbooden, N.V., Pala, M., Studer, C. and Bielders, C.L. (eds) (1999) *Efficient Soil Water Use: the Key to Sustainable Crop Production in the Dry Areas of West Asia and North and Sub-Saharan Africa. Proceedings of the Workshops Organized by the Optimizing Soil Water Use Consortium; Niamey, Niger, 26–30 April 1998 and Amman, Jordan, 9–13 May 1999*. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria, 490 pp.

El Beltagy, A. (2000) Strategic options for alleviating conflicts over water in dry areas. A paper presented at the Crawford Fund Sixth Conference on Food, Water and Wars: Security in a World of Conflict, 15 August 2000, Canberra, Australia.

English, M., Musick, J.T. and Murty, V.V.N. (1990) Deficit irrigation. In: Hoffman, G.J., Howell, T.A. and Solomon, K.H. (eds) *Management of Farm Irrigation Systems.* ASAE, St Joseph, Michigan, pp. 631–663.

Erskine, W. and Malhotra, R.S. (1997) Progress in breeding, selecting and delivering production packages for winter sowing chickpea and lentil. In: *Problems and Prospects of Winter Sowing of Grain Legumes in Europe, AEP Workshop, December 1996, Dijon*. AEP, France, pp. 43–50.

Gregory, P.J. (1991) Concepts of water use efficiency. In: Harris, H.C., Cooper, P.J.M. and Pala, M. (eds) *Soil and Crop Management for Improved Water Use Efficiency in Rain-fed Areas. Proceedings of an International Workshop, Ankara, Turkey 1989.* ICARDA, Aleppo, Syria, pp. 539–547.

Hamdi, A., Erskine, W. and Gates, P. (1992) Adaptation of lentil seed yield to varying moisture supply. *Crop Science* 34, 987–991.

Harris, H.C. (1991) Implications of climatic variability. In: Harris, H.C., Cooper, P.J.M. and Pala, M. (eds) *Soil and Crop Management for Improved Water Use Efficiency in Rain-Fed Areas. Proceedings of an International Workshop 1989, Ankara, Turkey.* ICARDA, Aleppo, Syria, p. 352.

Margat, J. and Vallae, D. (1999) *Water Resources and Uses in the Mediterranean Countries: Figures and Facts*. Blue Plan, Regional Activity Center, UNEP, Aleppo, Syria.

Nordblom, T. and Shomo, F. (1995) *Food and Feed Prospects to 2020 in West Asia/ North Africa Region*. Social Studies Paper No. 2, NRMP, ICARDA, Aleppo, Syria.

Oweis, T. (1997) *Supplemental Irrigation: a Highly Efficient Water-use Practice*. ICARDA, Aleppo, Syria, 16 pp.

Oweis, T. and Hachum, A. (2001) Reducing peak supplemental irrigation demand by extending sowing dates. *Agricultural Water Management* 50, 109–123.

Oweis, T. and Taimeh, A. (1996) Evaluation of small basin water harvesting systems in the arid region of Jordan. *Water Resources Management* 10, 21–34.

Oweis, T., Pala, M. and Ryan, J. (1998a) Stabilizing rain-fed wheat yields with supplemental irrigation and nitrogen in a Mediterranean-type climate. *Agronomy Journal* 90, 672–681.

Oweis, T., Oberle, A. and Prinz, D. (1998b) Determination of potential sites and methods for water harvesting in central Syria. *Advances in GeoEcology* 31, 83–88.

Oweis, T., Hachum, A. and Kijne, J. (1999) *Water Harvesting and Supplemental Irrigation for Improved Water Use Efficiency in the Dry Areas*. SWIM Paper 7, International Water Management Institute, Colombo, Sri Lanka.

Oweis, T., Zhang, H. and Pala, M. (2000) Water use efficiency of rain-fed and irrigated bread wheat in a Mediterranean environment. *Agronomy Journal* 92, 231–238.

Oweis, T., Prinz, D. and Hachum, A. (2001) *Water Harvesting: Indigenous Knowledge for the Future of the Drier Environments*. ICARDA, Aleppo, Syria.

Pala, M. and Mazid, A. (1992) On-farm assessment of improved crop production practices in northwest Syria: chickpea. *Experimental Agriculture* 28, 175–184.

Pala, M. and Studer, C. (1999) Cropping systems management for improved water use efficiency in dry-land agriculture. Paper presented at the International Conference on Water Resources Conservation and Management in Dry Areas, 3–6 December 1999, Amman, Jordan.

Pala, M., Matar, A. and Mazid, A. (1996) Assessment of the effects of environmental factors on the response of wheat to fertilizer in on-farm trials in a Mediterranean type environment. *Experimental Agriculture* 32, 339–349.

Rodriguez, A. and Thomas, N. (1999) *Mapping Rural Poverty and Natural Resource Constraints in Dry Areas*. Social Sciences Paper No 6, Natural Resources Management Programme, ICARDA, Syria.

Ryan, J. (ed.) (2000) *Plant Nutrient Management under Pressurized Irrigation Systems in the Mediterranean region. Proceedings of the IMPHOS International Workshop Organized by the World Phosphate Institute, 25–27 April 1999, Amman, Jordan*. ICARDA, Aleppo, Syria, 440 pp.

Seckler, D., Molden, D. and Barker, R. (1999) *Water Scarcity in the Twenty First Century*. Water Brief 1, IWMI, Colombo, Sri Lanka.

Singh, K.B. and Saxena, M.C. (1996) *Winter Chickpea in Mediterranean-type Environments. A Technical Bulletin*. ICARDA, Aleppo, Syria.

Singh, K.B., Malhotra, R.S., Saxena, M.C. and Bejiga, G. (1997) Winter sowing of chickpea in the Mediterranean region. *Agronomy Journal* 89(1), 112–118.

Studer, C. and Erskine, W. (1999) Integrating germplasm improvement and agricultural management to achieve more efficient water use in dry area crop production. Paper presented at the International Conference on Water Resources Conservation and Management in Dry Areas, 3–6 December 1999, Amman, Jordan.

Zhang, H. and Oweis, T. (1999) Water–yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. *Agricultural Water Management* 38, 195–211.

Zhang, H., Oweis, T., Garabet, T.S. and Pala, M. (1998) Water use efficiency and transpiration efficiency of wheat under rain-fed conditions and supplemental irrigation in a Mediterranean-type environment. *Plant and Soil* 201, 295–305.