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SWIM Paper

Water Harvesting and Supplemental Irrigation for Improved Water Use Efficiency in Dry Areas

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and
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SWIM

ICARDA

System-Wide Initiative on Water Management



SWIM Papers

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TAC designated IWMI, the lead CGIAR institute for research on irrigation and water management, as the convening center for the System-Wide Initiative on Water Management (SWIM). Improving water management requires dealing with a range of policy, institutional, and technical issues. For many of these issues to be addressed, no single center has the range of expertise required. IIMI focuses on the management of water at the system or basin level while the commodity centers are concerned with water at the farm and field plot levels. IFPRI focuses on policy issues related to water. As the NARS are becoming increasingly involved in water management issues related to crop production, there is strong complementarity between their work and many of the CGIAR centers that encourages strong collaborative research ties among CGIAR centers, NARS, and NGOs.

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Randolph Barker
SWIM Coordinator

SWIM Paper 7

**Water Harvesting and Supplemental
Irrigation for Improved Water Use Efficiency
in Dry Areas**

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The authors thank R. Barker and R. Sakthivadivel for their valuable comments on an earlier draft of this paper.

This work was undertaken with funds specifically allocated to the System-Wide Initiative for Water Management (SWIM) by the Ford Foundation, the Rockefeller Foundation, and the Governments of Australia, Denmark, France, Germany, and The Netherlands.

Oweis, T., A. Hachum, and J. Kijne. 1999. *Water harvesting and supplementary irrigation for improved water use efficiency in dry areas*. SWIM Paper 7. Colombo, Sri Lanka: International Water Management Institute.

/ productivity / water harvesting / water scarcity / agricultural production / poverty / water use efficiency / arid lands / water resources development / rain-fed farming / West Asia / North Africa / India /

ISBN: 92-9090-378-3

ISSN: 1028-6705

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The International Irrigation Management Institute, one of sixteen centers supported by the Consultative Group on International Agricultural Research (CGIAR), was incorporated by an Act of Parliament in Sri Lanka. The Act is currently under amendment to read as International Water Management Institute (IWMI).

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CGIAR Centers

CIAT	Centro Internacional de Agricultura Tropical
CIFOR	Center for International Forestry Research
CIMMYT	Centro Internacional de Mejoramiento de Maize y Trigo
CIP	Centro Internacional de la Papa
ICARDA	International Center for Agricultural Research in the Dry Areas
ICLARM	International Center for Living Aquatic Resources Management
ICRAF	International Council for Research in Agroforestry
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IFPRI	International Food Policy Research Institute
IIMI	International Irrigation Management Institute
IITA	International Institute of Tropical Agriculture
ILRI	International Livestock Research Institute
IPGRI	International Plant Genetic Resources Institute
IRRI	International Rice Research Institute
ISNAR	International Service for National Agricultural Research
WARDA	West Africa Rice Development Association

Abstract

The countries in West Asia and North Africa (WANA) will soon be diverting water from irrigation to supply their domestic and industrial needs, unless, they obtain substantial amounts of water from additional, untapped water resources. Some of these countries are already doing it, and hence agriculture is left each year with less water. The renewable water resource per capita in the WANA region is about one-sixth of the worldwide average. The chance, therefore, of reversing the trend of diminishing supplies to agriculture is extremely small. If agricultural production and livelihoods are to be sustained at current levels, the water available to agriculture will have to be used more productively.

The productivity of land and water in rain-fed areas can still be greatly enhanced through water harvesting and supplemental irrigation. Marginal lands with annual rainfall of less than 300 mm can be cultivated if controlled but limited additional water is made available. In many instances, such an incremental water supply can be provided through appropriate water harvesting techniques. However, the past experience with the introduction of water harvesting techniques into semiarid and arid countries has not been very promising. This paper aims to elucidate the likely reasons for these disappointments. The paper reviews the state of the art of both *water harvesting* (WH) and *supplemental irrigation* (SI) technologies in the temperate and subtropical dry lands with a Mediterranean-type climate.

Water harvesting (WH) is defined as the process of concentrating rainfall as runoff from a larger area for use in a smaller target area. The process is distinguished from irrigation by three key features: first, the “catchment” area is contiguous with the benefiting target area and is relatively

small; second, the application to the target area is essentially uncontrolled—the objective is simply to capture as much water as possible and store it within the reach of the plant(s), in the soil profile of a cultivated area or into some type of reservoir; third, water harvesting can be used to concentrate rainfall for purposes other than crop production. Several different types of WH are identified and discussed.

Supplemental irrigation (SI) is defined as the application of a limited amount of water to the crop when rainfall fails to provide sufficient water for plant growth to increase and stabilize yields. The additional amount of water alone is inadequate for crop production. Hence, the essential characteristic of SI is the supplemental nature of rainfall and irrigation. It is well documented that the *water productivity* (WP) (i.e., the ratio of economic yield of a crop and the total amount of water consumed) of rain and supplemental irrigation exceeds the *water productivity* of either component if applied alone. Several examples of increased WP as a result of the introduction of SI in rain-fed lands are presented.

Most of the examples of WH and SI are drawn from studies carried out in the WANA region, with some references to the work done in Sub-Saharan Africa and India. The emphasis is on the technical aspects, but it should be realized that the success or failure is at least as much determined by the prevailing socioeconomic conditions of the area. Acceptance of the new technology by the water resource users is seen to depend largely on their early and sustained involvement in the development and implementation of the technique and the perceived notion of risk and profitability by

farmers. In addition, there are environmental issues, such as declining water tables, which are frequently overlooked in the design and implementation of WH and SI projects. Three

case studies (see annex) illustrate some of the constraints associated with the adoption of WH technologies. The paper concludes with a set of recommendations and research needs.

Water Harvesting and Supplemental Irrigation for Improved Water Use Efficiency in Dry Areas

Theib Oweis, Ahmed Hachum, and Jacob Kijne

Introduction

Dry areas occupy over 95 percent of the total lands of West Asia and North Africa (WANA) region. The area is dominated by a Mediterranean-type climate characterized by cool and rainy winters and temperate dry summers. Mediterranean sub-climates are usually differentiated by the length of the summer drought period and the temperatures during winter and summer. In general, these areas are characterized by low rainfall amounts (100 mm to 600 mm annually) and have limited renewable water resources.

Presently, over 75 percent of the available water in WANA is used for agriculture. However, the competition for water from other users leaves agriculture each year with reduced amounts. If agricultural production and livelihoods are to be sustained, even at current levels, increasing the productivity of water in agriculture in dry areas becomes a crucial issue—we must produce more with less. Water harvesting and supplemental irrigation are especially important in the WANA region, because this region has to either divert water from irrigation to supply their domestic and industrial needs (group 1, as defined by Seckler

et al. 1998), or develop substantial amounts of additional water resources to meet reasonable future requirements (group 2).

This paper aims to describe the state of the art of both water harvesting (WH) and supplemental irrigation (SI) techniques in the temperate and sub-tropical dry lands, especially in the countries of WANA that are characterized by a Mediterranean-type climate. In addition, three case studies of water harvesting are presented (see annex). These were selected from the case studies presented at the FAO Expert Consultation Cairo (1994). By sharing with us the success and the failure of these endeavors, the authors of the case studies illustrate many of the points that are made in the text. They also illustrate how difficult it is to successfully introduce new technologies to farmers, who at the outset are not usually familiar with the intended purpose of the changes. Also, this paper emphasises that it is difficult to assess the potential for adoption without more studies to assess the risks and economic returns of the alternative techniques and practices.

Water Harvesting and Supplemental Irrigation—Definition of Terms

In this section, we define and discuss the concepts of water harvesting and supplemental irrigation and attempt to clarify the confusion that exists in the literature. The confusion seems to

arise in part because these two practices are at times used conjunctively. However, SI is usually practiced in the wetter part of the dry areas (300–600 mm annual rainfall). On the other hand,

WH is practiced in the drier areas (100–300 mm annual rainfall), where crops cannot grow depending only on rainfall.

Water Harvesting

Water harvesting, defined in its broadest sense as the collection of runoff for its productive use (Siegert 1994), is an ancient art practiced in the past in many parts of North America, Middle East, North Africa, China, and India. More specifically, in crop production, *water harvesting* is essentially a *spatial* intervention designed to change the location, where water is applied to augment evapotranspiration that occurs naturally. It is relevant to areas where the rainfall is reasonably distributed in time, but inadequate to balance potential evapotranspiration (ET) of crops.

More precisely, water harvesting can be defined as the process of concentrating rainfall as runoff from a larger catchment area to be used in a smaller target area. This process may occur naturally or artificially. The collected runoff water is either directly applied to an adjacent agricultural field (or plot) or stored in some type of (on-farm) storage facility for domestic use and as supplemental irrigation of crops. Water harvesting is generally feasible in areas with an average annual rainfall of at least 100 mm in winter rains and 250 mm in summer rains.

Agriculture in the dry areas depends on the vagaries of weather, especially of the rain. The dry areas are characterized by low annual rainfall, the distribution of which varies in space and time. Without doubt, the greatest climatic risk to sustained agricultural production in these areas is rainfall variability, which unfortunately is usually greater in zones of lower mean annual rainfall. Two distinct zones can be identified within the dry areas. The first zone is relatively wetter, where annual rainfall is sufficient to support continuous and economic cropping

systems during the rainy season without irrigation. This zone is usually dominated by rain-fed farming. Rainfall in this zone is marginal in relation to water requirement, but its distribution is poor and water stress often occurs during one or more stages of crop growth, lowering the yield. Thus, the productivity of rainfall is low, even though much of it may be utilized by crops. Variations in rainfall from one year to the next create instability in production, and risk-averse farmers are unwilling to invest in fertilizers and other inputs that are needed for high levels of productivity.

The second zone in the dry areas is characterized by an annual rainfall of less than 300 mm which is too low to support continuous cropping with a reasonable economic value. Much of the dry areas lies in this zone. Small and scattered rainstorms fall on land that is generally degraded with poor vegetative cover and infertile soil. These areas have been exposed to mismanagement, overgrazing, removal of bushes for fuel wood, and are subject to desertification. Rainfall, although low in annual average, when multiplied by the vast areas amounts to a large volume of water. Although it constitutes a major resource, it is lost almost completely through direct evaporation or through uncontrolled runoff. Thus, rainfall without intervention is nearly useless in these areas. However, economic agricultural production can be achieved by concentrating the water into smaller areas through water harvesting techniques. Indigenous and modern WH systems make water available to supplement rainfall for winter crops and as a sole source of water for summer crops.

Water harvesting supports a flourishing agriculture in many dry areas, where rainfall is low and erratic in distribution. Examples are given, among others, by Oweis and Taimeh (1996), Rees et al. (1989), Suleman et al. (1995), Katyal et al. (1993), Perrier (1990), Carmona and Velasco (1990), Oswal (1994), and Krishna, Arkin, and Martin (1987). However, for any agricultural

water development to be successful, it must be economically sustainable. The sustainability of the various water harvesting techniques is found to depend largely upon the timing and the amount of rainfall (Cohen et al. 1995; Rodriguez 1997; Boers and Ben-Asher 1982).

As mentioned, some WH techniques are of ancient origin. As the appropriate choice of technique depends on the amount of rainfall and its distribution, soil type and depth, land topography, and local socioeconomic factors, these systems tend to be very site-specific. Different indigenous techniques and systems were developed in different parts of the world, and they are still referred to in the literature by their traditional names. Among these are *Haffir* and *Teru* in Sudan, *Gessour* in Tunisia, *Khadin* or *Tank* in India, *Lacs Calinaires* in Algeria, *Caag* and *Gawans* in Somalia, *Sayl* in Yemen, *Khuls* in Pakistan, and *Boqueras* in Spain (see e.g., Hudson 1987; van Dijk and Ahmed 1993; Reij 1991; Kolarkar, Murthy, and Singh 1983; Achouri 1994; Prinz 1994a; Giraldez et al. 1988; and Oweis 1996). A good historical review of rainwater harvesting for agriculture is given in UNEP (1983).

Ancient water harvesting systems are characterized by flexibility and endurance. Flexibility is demonstrated by their easy integration with other resource use systems as well as by their widespread adoption by diverse cultural groups in various part of the world. Endurance is shown by their antiquity and their capacity to persist in the face of abrupt changes in the social order. The labor requirements were appropriately modest, mostly within the capabilities of individual household or small communities. The indigenous techniques are strongly associated with the people who live in marginal environments. These techniques comprise water and soil moisture control at a very simple level, often involving no more than the placement of a rigid row of rocks along the contours of slopes and wadis capturing the surface runoff and trapping the silt.

The worldwide potential for the introduction of water harvesting techniques has not been fully assessed, but especially in the WANA region, this potential is probably quite large (Oweis and Prinz 1994). But not only in WANA; also in the drier areas of India, such as the Deccan plateau of central India, the western regions of Rajasthan and Gujarat, and Bihar, water harvesting remains an important source of water for agriculture (Kolavalli and Whitaker 1996). Besides for agriculture, rainwater is harvested in Gujarat for domestic use and to recharge groundwater aquifers.

Although the revival of water harvesting techniques began in the early 1930s, little construction and research activity began before the late 1950s as pointed out by Frasier and Myers (1983). In the 1960s, various governmental, private, and university research organizations, particularly in arid and semiarid areas, initiated studies to develop and evaluate new methods and materials for designing, constructing, and managing water harvesting with lower installation costs and improved system reliability. As a result, new terms and names related to water harvesting techniques have appeared in the literature during the last two decades (e.g., Critchley and Siegert 1991; Prinz 1994a). Recently, a renewed interest in water harvesting is shown in Sub-Saharan Africa, probably as a result of increasing pressure on the land, which forces more and more people into dry areas (Rey 1998, personal communication).

Although the term water harvesting is used in different ways, the following are among its characteristics:

1. It is practiced in arid and semiarid regions, where surface runoff often has an intermittent character.
2. It is based on the utilization of runoff and requires a runoff producing area and a runoff receiving area.

- Because of the intermittent nature of runoff events, storage is an integral part of the water harvesting system. Water may be stored directly in the soil profile or in small reservoirs, tanks, and aquifers.

Each WH system should therefore have the following four components: (a) runoff producing catchment, (b) runoff collection scheme, (c) runoff storage facility, and (d) cultivated or cropped area. There is a general agreement that the first two components are found in all water harvesting systems. The confusion starts with component (c). This component raises three important questions:

- Is the runoff water stored in a surface reservoir (pond, tank, etc.) or directly in the soil profile?
- Is the collected runoff water applied to the cropped area immediately after collection (during rainfall) or later (may be days) after collection?
- If the collected runoff water is stored in a surface reservoir for subsequent use as supplemental irrigation, are the cultural

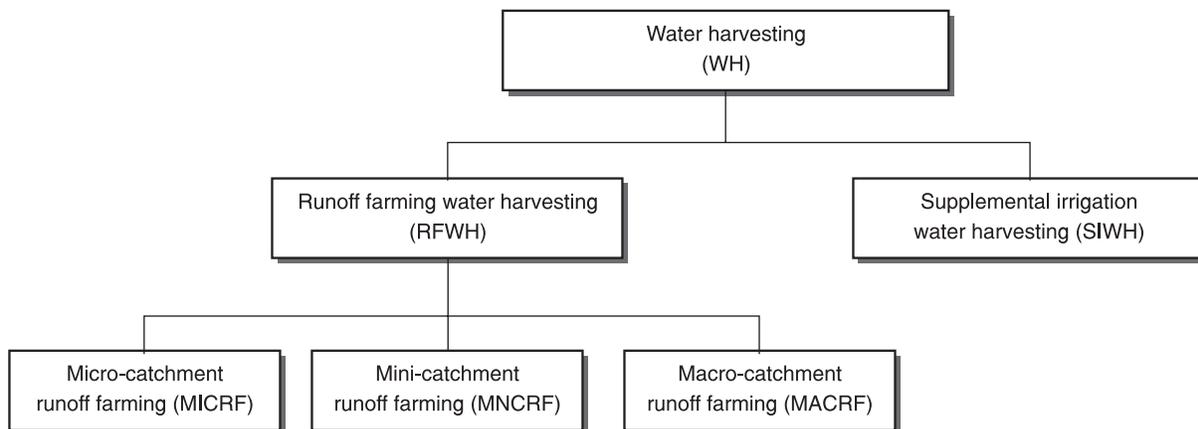
practices of the crop the same as under irrigated conditions?

To facilitate the presentation of the various types of water harvesting techniques, the following classification, based on the type of storage, is adopted and shown in figure 1. The various forms of runoff farming water harvesting (RFWH) will be discussed in another section. In addition to supplemental irrigation water harvesting (SIWH) shown as a subcomponent under WH in figure 1, supplemental irrigation (SI) can be practiced independently of water harvesting.

Supplemental Irrigation

Supplemental irrigation is a *temporal* intervention, designed to influence when water is made available to augment natural evapotranspiration. It is irrelevant when daily rainfall is often adequate to support crop growth, but there are frequent periods of shortage, during which the crop would die, or yields would be substantially depressed by moisture shortage. Such a state clearly requires either surface storage, or exploitation of groundwater. Where water is

FIGURE 1. Proposed classification of water harvesting techniques.



limited in relation to land, supplemental irrigation will be desirable because the productivity of rainfall (which would otherwise evaporate straight back from the bare soil, or would be transpired by noneconomic crops) is increased by the addition of relatively small amounts of water which assure the survival of an economically valuable crop. However, success or failure of water harvesting and supplemental irrigation systems depends at least as much on how much attention is given to the social and economic issues associated with the introduction of new techniques.

Supplemental irrigation is defined as the application of a limited amount of water to the crop when rainfall fails to provide sufficient water for plant growth, to increase and stabilize yield. The additional water alone is inadequate for crop production (Oweis 1997; Arar 1992). The major constraint in crop production in Mediterranean-type climates is insufficient soil water in the root zone to meet crop water requirements. Periods of severe water stress are very common and often coincide with the most sensitive stages of growth. Therefore, water supplied through supplemental irrigation, if applied in the right amount and at the right time, can make a crucial difference in the yield potential of common crops.

Characteristics of SI in rain-fed areas include the following:

1. Water is applied to rain-fed crops which is normally produced without irrigation.
2. It is applied only when rainfall is inadequate, because rainfall is the prime source of water for rain-fed crops.
3. The amount and timing of SI are not meant to provide water stress-free conditions over the growing season, but to provide enough water during the critical stages of crop growth to ensure optimal yield in terms of yield per unit of water (Oweis 1997).

It has also been said that SI aims to increase the total farm yield and water use efficiency by maximizing the area that benefits from the water available (Caliandro and Boari 1992). These two objectives are often contradictory: maximizing the cultivated area usually comes at the cost of providing an optimal amount of water to the crops during the sensitive stages. The preferred objective of SI is to optimize yield per unit of water, which implies the effect of water stress on crop yield during the various growth stages.

One example of the variable effect of water stress on yield is given here, but the topic will again be discussed in a later section. Wheat is the crop most commonly grown with SI in many Mediterranean countries. Reported experimental results indicate that water-stress conditions at different growth stages cause different adverse effects on crop yield. In southern Italy, when the October–December period was dry, but the following January–May period was rather wet, one irrigation immediately after sowing resulted in a grain increase of 132 percent (from 2.03 tons/ha to 4.71 tons/ha). However, irrigation only at the booting stage increased yield by just 23 percent (from 2.03 tons/ha to 2.50 tons/ha), as reported by Caliandro and Boari (1992).

Potentially, SI may have three major effects: (1) yield improvement, (2) stabilization of production from year to year (increasing reliability), and (3) providing the conditions suitable for economic use of higher technology inputs, such as high yielding varieties, fertilizers, and herbicides, irrespective of seasonal rainfall. At Tel-Hadya, Syria, where International Center for Agricultural Research in the Dry Areas (ICARDA) has been conducting supplemental irrigation research for over 8 years, SI increased the average rain-fed wheat yield from 2.25 tons/ha to 5.9 tons/ha. In the dry year of 1988–1989, when the total rainfall was 234 mm, the yield was increased from 0.74 tons/ha to 3.83 tons/ha using 183 mm of SI. By contrast, in the wet year of 1987–1988 (504 mm rainfall), the yield was increased from 5.04 tons/ha to 6.44 tons/ha

by 75 mm of SI (Oweis 1997). In an average year (316 mm rainfall), the rain-fed yield was increased from 2.3 tons/ha to 5.6 tons/ha by adding 120 mm of SI. In field demonstrations, conducted by ICARDA under farmers' conditions in Syria since 1988–1998, the mean wheat yield increased from less than 0.8 tons/ha under rain-fed conditions to more than 4.8 tons/ha with SI.

Similar improvements have been reported from many countries such as Jordan, Iraq, Tunisia, and Morocco (Perrier and Salkini 1991). In Central Anatolia, Turkey, average wheat yield has greatly improved by applying SI. For example, in Konyo Province, rain-fed yield ranged from 0.9 tons/ha to 2.5 tons/ha, and from 3 tons/ha to 4.5 tons/ha with SI; and in Eskisehir Province, yields increased from 1.1 tons/ha to 3.2 tons/ha (rain-fed) to 2.5 tons/ha to 6.25 tons/ha with SI (Tenkinel et al. 1992). Islam and Bhuiyan (1991) reporting the results of 8 years of experiments in Bangladesh, indicated that the impact of SI depends mainly on the rainfall distribution pattern and magnitude of the last rainfall of the season. Generally, late transplanted rice suffered from water stress when the rains ended early. In this situation, one timely SI of 60 mm produced 58 percent more yield.

The stabilizing effect of SI on yield was shown, for example, by the change in the coefficient of variation (CV) of grain yields obtained during the experimental SI research of 5 years at ICARDA, where the CV was reduced from 71 percent (rain-fed) to 8 percent (SI). On farmers' demonstration fields,¹ the CV dropped in SI fields from 100 percent to 10 percent (Salkini and Ansell 1992).

All possible sources of water can be used for SI systems, including treated industrial waste water, but here the focus of attention will be on water obtained in water harvesting. When the water supply comes from a water harvesting system, the size of the storage facility and the

release of water are the key design and management issues.

Palmer, Barfield, and Haan (1982) presented a simulation model combining watershed runoff and a crop yield model to determine the required size of the reservoir to ensure the availability of water on a sustainable basis for SI. Another, somewhat similar model was developed by Chotisasitorn and Ward (1976). The outputs of the model included, among others, the optimal sowing date of wet season crops in relation to the preceding rainfall pattern. Gwinn and Ree (1975) addressed the problem of the dependable water yield from a reservoir with intermittent inflows. The most efficient use involved brief periods during which the reservoir was empty. However, this condition would require an exact forecast of runoff, evaporation, seepage losses, and water use—an impossible requirement. Therefore, a minimum pool level in dry years is usually recommended for design and operation purposes. Mehta and Goto (1992) presented a model for sizing and operating an on-farm irrigation pond. The model determines the required minimum storage capacity at a desired reliability level with a given intake operation rule to meet fluctuating water demands. They concluded that on-farm irrigation ponds could reduce both waste of water and deficit by 20 to 30 percent, when compared with irrigation without an on-farm storage.

Senga (1991) pointed out that there are usually two objectives in operating a reservoir for SI: (a) promotion of effective release of water for crop production and (b) restriction of release as a precaution against drought. These two targets conflict with each other, indicating the complexity and difficulty of operating a reservoir for SI.

Where groundwater is the major source of water for SI, overexploitation of the resource is a serious problem. For example, current utilization of groundwater in Aleppo, Syria, leads to an

¹These are demonstration plots established at farmer's fields and jointly managed by farmers and the extension services to help the adoption of improved SI technology.

annual lowering of the water table, and hence an increase in the pumping depth of 1 meter/year to 2 meters/ year (Salkini and Oweis 1994). These SI systems are obviously not sustainable, unless effective measures are taken to balance the withdrawals with the recharge. Rodriguez (1997), who conducted a comprehensive assessment of

the sustainability of agricultural groundwater management in Syria, estimated that only 30 to 40 percent of the groundwater used in agriculture is recharged or renewed. Deep non-flowing artesian wells are degrading the good quality water of shallow wells, and most of the shallow wells are running dry.

Runoff Farming Water Harvesting

When the collected runoff water is diverted directly into the cropped area during the rainfall event, the technique is called runoff farming water harvesting. Generally, the quantity of runoff exceeds the infiltration capacity of the soil. Therefore, ridges, borders, or dikes are placed around the cropped area to retain the water on the soil surface. Overflow from fields may be conveyed by channels for use on other lower fields.

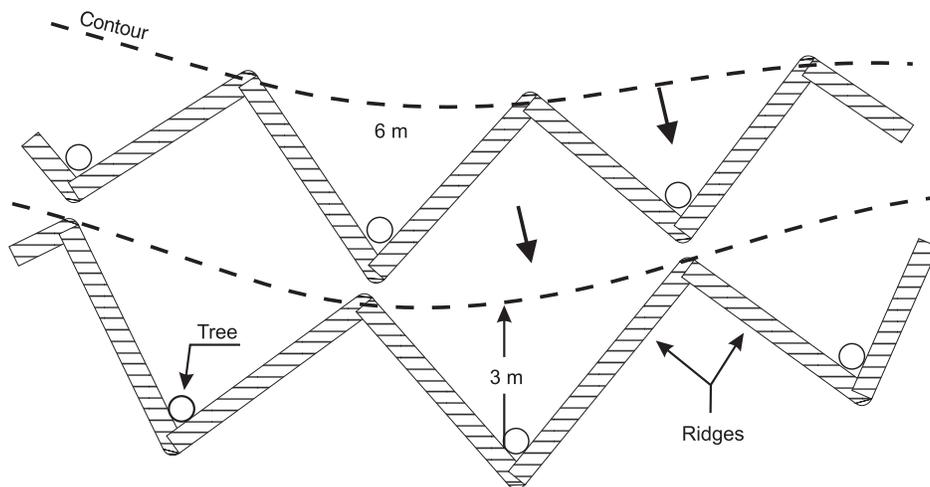
The following are the characteristics of RFWH:

1. The absence of surface storage; the soil profile serves as water reservoir.

2. The collected runoff water is directly applied to the cropped area.
3. The cultural practices (seedbed preparation, plant rows spacing and population, field layout, etc.) are in accordance with the catchment characteristics (size, slope, etc.) and the expected timing of runoff events.

A further differentiation is based on the size of the water harvesting system (see figure 1). Size governs the type of crops that can be grown. Micro-catchment runoff farming systems are primarily used for trees and are characterized by a relatively small runoff producing catchment

FIGURE 2.
Micro-catchment runoff farming water harvesting.



(figure 2). Mini-catchment runoff farming systems are primarily used for row crops or strips of annual crops, and the runoff producing catchment is a long strip (figure 3). In both systems, water from the catchment area runs directly into the cropped area. The catchment usually receives an appropriate treatment regarding shape, configuration, surface condition, and runoff inducement practices.

Macro-catchment runoff farming refers to large-scale rainwater harvesting. This may be the diversion of a natural wadi, a stream in a gully, or a wadi flowing from a natural catchment (usually untreated). The collected flow is immediately diverted by a diversion structure to flood irrigate an adjacent agricultural field as shown in figure 4 (see Kolarkar, Murthy, and Singh 1980; Carter and Miller 1991). This method is suitable for all kinds of crops (trees, row crops, and closely growing crops). The catchment should be big enough to provide the needed irrigation water. The diversion structure may consist of a stone barrier across the

wadi or the intermittent stream. When the rain water flows into the wadi, it will be slowed down and diverted from its course in the stream channel to flow over the rather broad flat floodplain bordering the wadi. Strategic placement of rock barriers and crops will allow the maximum use to be made of the floodwaters with the minimum damage to land and crops. Careful design and layout are necessary to withstand floods and prevent erosion.

Most of the published research work on modeling and design of RFWH systems is on the micro-catchment scale (Boers et al. 1986a; Oron and Enthoven 1987). However, these models can also be applied to the mini-catchment RFWH systems and may be adjusted and extended to the macro-catchment RFWH systems. Among the models are those of Perrier (1988), Giraldez et al. (1988), Sharma (1986), Sharma, Pareek, and Singh (1986), Boers et al. (1986a), Oweis and Taimah (1996), and Cohen et al. (1997). Figure 5 shows a general conceptual model for RFWH systems.

FIGURE 3.
Mini-catchment (strip) runoff farming water harvesting.

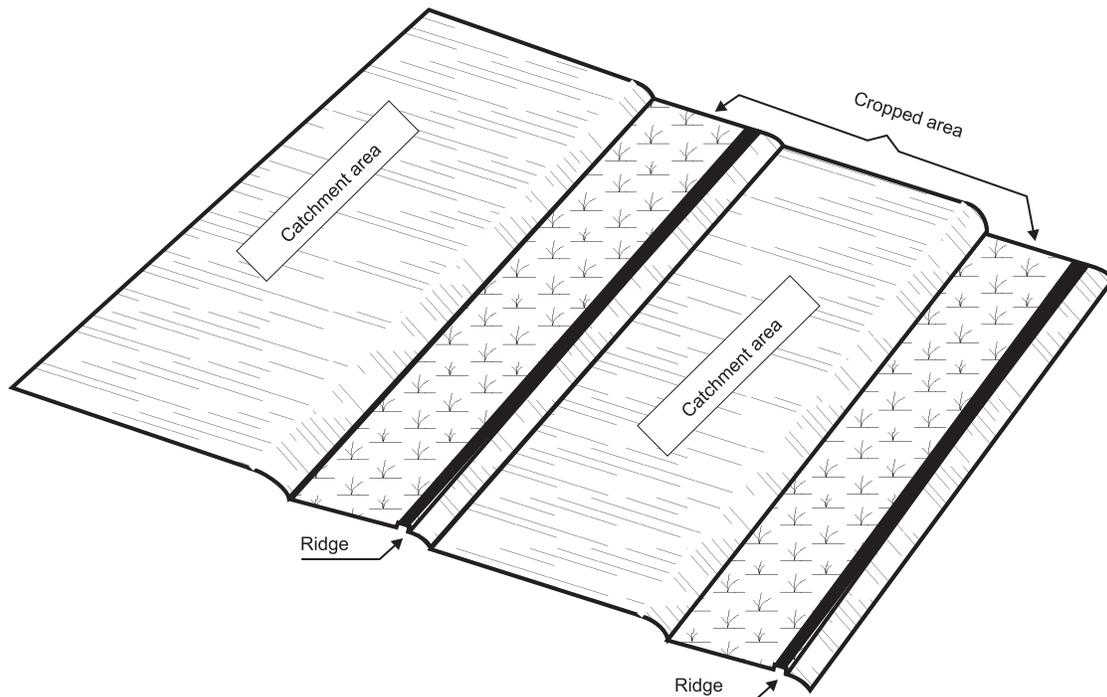


FIGURE 4.
Macro-catchment runoff farming water harvesting.

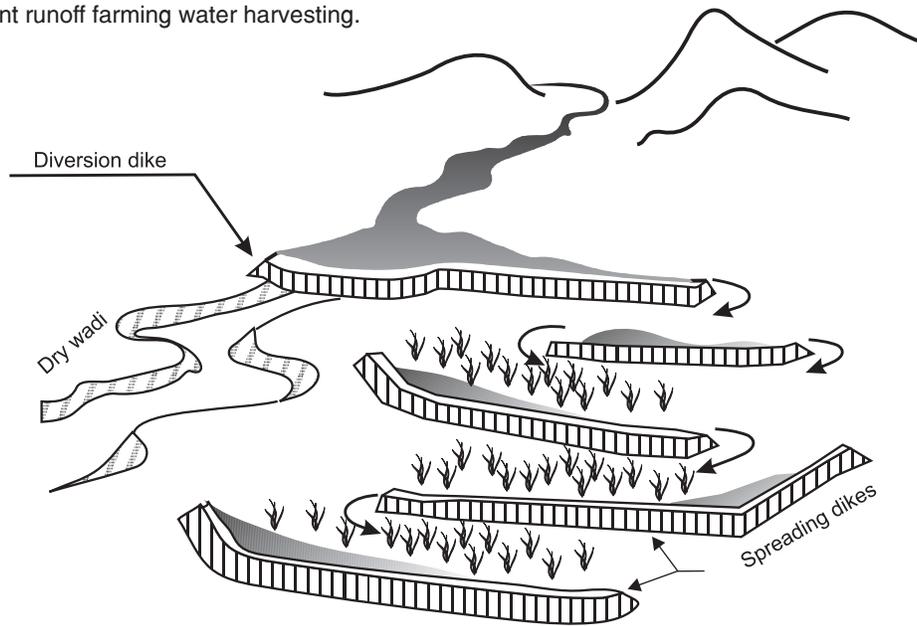
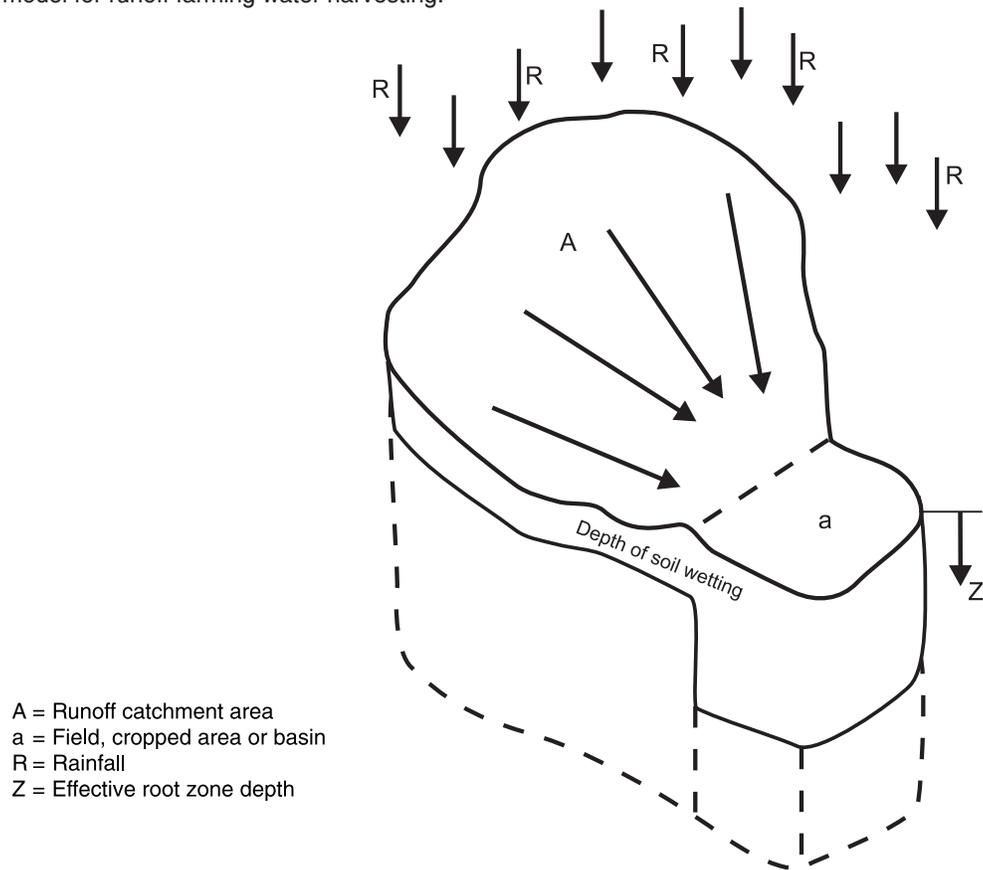


FIGURE 5.
Conceptual model for runoff farming water harvesting.



The basic design input for RFWH systems includes:

1. Topography of the area.
2. Soil type, including texture and water retention capacity, soil depth, infiltration characteristics, and hydraulic conductivity.
3. Climate, including daily rainfall for a reasonable number of years (at least 15), evaporation, transpiration, either measured or computed from climatic data such as temperature, solar radiation, humidity, wind, vapor pressure deficit, etc.
4. Crop, including rooting depth, growing season, critical stages of growth, and spacing.

The basic design equation is the water balance applied to the cropped area, a , in figure 5 for any defined period of time as follows:

$$SW_i + R + U - E - T - D = SW_{i+1} \quad (1)$$

where,

SW_i, SW_{i+1} = depth of water stored in the root zone of the cropped area at the beginning and end of the time period, respectively.

R = amount of rainfall (depth) falling on the cropped area during the same time period.

U = depth of runoff collected (from rainfall on catchment A) on the cropped area during the time period.

E = soil surface evaporation expressed as depth of water lost from the cropped area during the time period.

T = transpiration of the crop expressed as depth of water lost from the cropped area during the time period.

D = depth of deep percolation below the effective depth of the plant root zone during the time period.

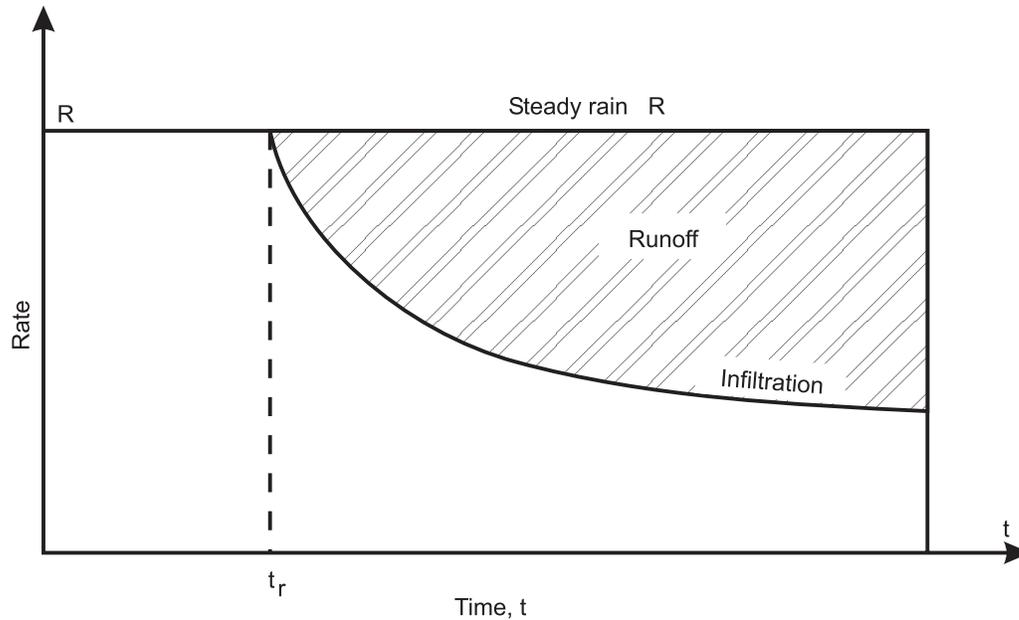
The most complex and difficult component of the model of equation 1 is the element U . According to Boers (1994), the success or failure of rainwater harvesting depends to a great extent on the quantity of water that can be harvested from an area under given climatic conditions. Most of the proposed rainwater harvesting models pay much attention to this component. However, the available procedures and methods for evaluating U are still empirical and far from complete.

The depth of collected runoff U for a given rainfall event depends upon a long list of variables (Hachum and Alfaro 1980; Morin and Kosovsky 1995; Pruski et al. 1997). The following are among the more important ones:

1. Rainfall event characteristics; amount and intensity-time distribution.
2. Soil type; infiltration characteristics, cracking.
3. Slope of the catchment.
4. Size of the catchment; length along the down slope.
5. Antecedent water content of the soil in the catchment, as it affects the infiltration rate.

Figure 6 shows the infiltration and runoff of the catchment area under a steady rain with rate, R . The threshold retention of a catchment is the amount (i.e., depth) of rainfall required for wetting, infiltration, and filling of the surface storage capacity of the catchment before the initiation of runoff. Oweis and Taimah (1996) reported a threshold value of 2.2 mm at a research station in Jordan. Perrier (1988) suggested values between 3–6 mm depending on the surface conditions of the catchment. The most comprehensive

FIGURE 6.
Infiltration and potential runoff of a catchment under steady rain rate, R.



treatment of the threshold retention of a catchment is presented by Sharma, Pareek, and Singh (1986) for a catchment that was compacted after the first rain of the season by a sheep foot roller. The soil of the catchment was a deep loess with a loamy sand texture (81% sand, 8% silt, and 11% clay). During a seven-year study, the threshold rainfall was initially large (4.7–6 mm) due to large infiltration rate and surface storage capacity. However, the threshold value gradually decreased to 2–3 mm, as a soil crust had formed and hardened. It is obvious that runoff increases as the rainfall threshold value decreases. Boers (1994) used a computer model to study the effect of the threshold value on the volume of runoff from a 20 m² catchment. Runoff volume was 22.9 m³, 21.4 m³, and 20.1 m³ for threshold values of 4 mm, 5 mm, and 6 mm, respectively.

Runoff Coefficient

The runoff coefficient of a catchment is the ratio of runoff volume to rainfall volume. In figure 6, the runoff coefficient is given by the ratio of the

hatched area to the total rectangular area ($R \cdot t$). If the runoff coefficient is E_r , then the depth of runoff water collected and supplied to the cropped area will be:

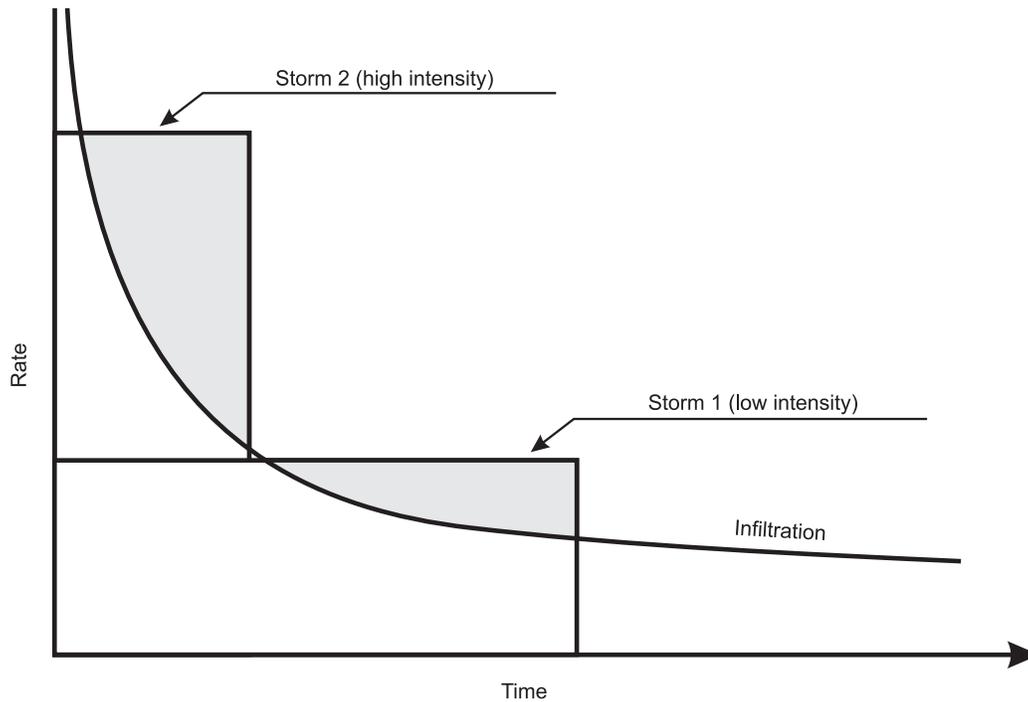
$$U = (A \cdot R \cdot E_r) / a \quad (2)$$

in which, U and R are as defined in equation 1, A is the area of the catchment in square meters, and a is the cropped plot in square meters.

Both rainfall intensity and distribution greatly affect runoff coefficient. Unfortunately, data on rainfall intensity are scarce in arid and semiarid regions. Usually, only the daily rainfall data from a sufficient period of years are available for the system design. Theoretically and experimentally, each steady rainfall rate corresponds to a specific runoff coefficient value provided the rainfall intensity exceeds the infiltration rate of the soil and all other factors in the system remain the same. To illustrate this, figure 7 shows a simplified representation of infiltration and the potential surface runoff (grey areas) under two different storms having equal amounts of rain. If this amount of rain is taken as one unit,

FIGURE 7.

Simplified representation of infiltration and potential surface runoff (grey areas) under two storms with equal amount of rain.



then the hatched areas, smaller than one, represent the potential runoff coefficient for each storm.

More water is lost as infiltration in a catchment with cracking soil under higher rainfall intensities than under lower intensities for the same depth of rainfall. Research is needed to characterize the hydrological behavior of small catchments (< 1–5 ha) and to develop simple, accurate, and practical techniques for estimating the runoff coefficient under varying rainfall conditions, soil surface conditions, soil type, slope, catchment geometry, and antecedent soil moisture. Undoubtedly, these variables act independently but also interact in their effect on the runoff coefficient. For example, Oweis and Taimah (1996) reported the runoff coefficient at a site in Jordan ranging from 6 percent to 77 percent for natural bare soil depending on both the rainfall and the size of the catchment. Rainfall intensity was not measured in their

fieldwork, but it is known to affect the resulting runoff. The average runoff coefficient for 25 m², 50 m², and 75 m² catchments for all storms were 55.9 percent, 37.6 percent, and 21.7 percent, respectively, confirming the expected decrease with an increase in the catchment size. The soils at their site are highly calcareous (60%), having a strong platy structure and high silt content. A surface crust usually forms after rainfall, resulting in very low infiltration rates and consequently, relatively high runoff coefficient.

The following linear regression equation has also been suggested to relate runoff with storm size:

$$U_c = B (R - R_0) \quad (3)$$

where,

U_c = depth of runoff averaged over the catchment area itself.

R_o = the threshold rainfall, as discussed earlier.

B = slope of U_c versus R line, the runoff coefficient of the catchment after the threshold rainfall has been exceeded (Sharma, Pareek, and Singh 1986).

For a given catchment area, B in equation 3 is expected to increase and R_o to decrease with time, as the soil surface becomes more crusted and compacted under the impact of rainfall. Figure 8 illustrates equation 3 for a small catchment (< 1 ha) at two different times, several years apart. Current knowledge is that B decreases with an increase in the size of the catchment and the length of slope. Also, B increases with an increase in slope, but there is a critical slope beyond which runoff volume and B are not affected by slope. For example, Sharma (1986) found that B ranged from 0.13 to 0.32 for a 0.5 percent slope; 0.36 to 0.45 for a 5 percent slope; and 0.26 to 0.44 for a 10 percent slope.

The runoff coefficient depends on the catchment size, where the former is a design

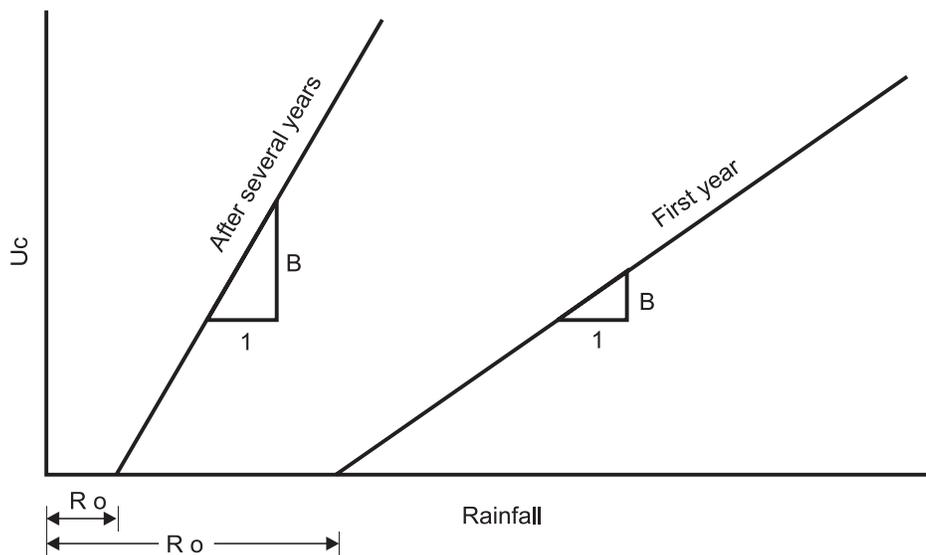
input and the latter, a design output. The design of a WH system is not straightforward; it is rather a trial and error procedure. If there is a constraint on land, the design problem becomes one of optimization to minimize the catchment area and maximize the net economical return.

From a linear regression analysis of 40 sets of runoff data from desert catchments, 100–120 m² in size with clay loam soil of eolean origin, Boers (1994) reported values for slope B in equation 3 ranging from 0.53 to 0.58 and values of threshold rainfall between 2.1 mm and 3.2 mm. Catchment surfaces in these experiments are bare and crusted, without deep depressions and a slope of 1 percent to 2 percent.

Rainfall Analysis

The importance of rainfall analysis for the prediction of runoff has been mentioned above. Perrier (1988) analyzed 28 years of rainfall data in a Mediterranean-type climate with a mean annual rainfall of 278 mm. With a rainfall

FIGURE 8. Linear model of runoff versus rainfall for a small catchment (< 1 ha) at two different times several years apart.



threshold value of 6 mm, the average annual number of runoff-producing storms was 15. The average monthly number of runoff producing storms was 1 in October, 1 in November, 3 in December, 3 in January, 2 in February, 2 in March, 2 in April, and 1 in May. However, the coefficient of variation for the number of runoff-producing storms for May was 160 percent, indicating that there are many years in which May has no runoff producing storms at all. Perrier (1988) suggested that WH design should be based on the rainfall analysis of the wettest month (January for the area under consideration), with a probability of 10 percent (i.e., return period of 10 years). He justified this recommendation by pointing out that the 10-year recurrence rainfall is usually adequate for a design of a storage facility and that the 10-year recurrence rainfall for the month with maximum rainfall is about double its mean monthly rainfall.

Useful rainfall parameters for the design of RFWH systems include:

1. Number of days in which the rain exceeds the threshold rainfall of the catchment, on a weekly, ten days, or monthly basis.
2. Probability and recurrence (in years) for the mean monthly rainfall.
3. Probability and recurrence for the minimum and maximum monthly rainfall.
4. Frequency distribution of storms of different specified intensities.

Many, for instance, Boers (1994) have suggested using average rainfall values (i.e., return period of 2 years) in the design. Thus, the WH system would fail to meet the crop water demands on average one year out of two. A better approach to determine the most appropriate return period is through modeling and economic analysis. Frasier (1990), among others, pointed out that the use of mean rainfall values

could be very misleading in designing a RFWH system. Any variability in the timing and quantity of rainfall events is transformed into variability in the quantity of the runoff collected and hence in the water availability for plant growth.

Area Ratio

Area ratio (r) is defined as the ratio of the catchment area (A) to the cropped area (a) as illustrated in figure 5. It is the most important output in the design of RFWH systems, integrating the effects of runoff coefficient, rainfall characteristics, soil, and crop factors. The commonest values are less than 10, but for macro-catchment RFWH systems this ratio may be in the order of hundreds (Prinz 1994b). In a dry desert climate with an annual rainfall of less than 100 mm, a value of 20 has been reported (Khan n.d.).

The best way to select the right area ratio for a given set of conditions is by system simulation. The parameters in equation 1 and hence the behavior of the water balance in the WH system are monitored daily. Different values for the area ratio are then tried. The simulation process is repeated for each value until the design criteria are met. One possible design criterion, as suggested by Oweis and Taimeh (1996), is to secure a full soil reservoir in the cropped area at the end of the rainy season assuming the maximum runoff storage coefficient (see next paragraph). Another criterion, according to Frasier (1990), is to relate the reduction in plant growth and crop production with the level of water depletion in the root zone, recognizing that the crop may die during the extended dry period. This criterion can simulate the interactions of the area ratio with the timing and amounts of rainfall events, soil water holding capacities, crop water requirements, and the plant rooting depths.

A simple calculation of the area ratio can be made to determine the feasibility of a runoff farming system in case of a deep root zone and

high water storage capacity of the soil (i.e., assuming the absence of deep percolation below the root zone). A rough and first order approximation for the area ratio (r) can be found from the following equation:

$$r = A/a = (ET + W_e - W_o - S) / S * E_r \quad (4)$$

where,

ET = estimated seasonal evapotranspiration of the crop.

W_e = available water in the entire root zone at the end of the season (i.e., in excess of the permanent wilting point).

W_o = available water in the soil to the same depth, at the beginning of the season.

S = the design seasonal rainfall.

E_r = runoff coefficient of the system.

Equation 4 is based on the assumption that no deep percolation occurs below the root zone of the crop. To illustrate, the following numerical example is given: If ET = 500 mm, $W_e = W_o$, S = 200 mm, and $E_r = 0.30$, then from equation 4, the area ratio is equal to 5. If there is any available water in the root zone due to the pre-growing season, $W_o = 90$ mm, and if there is no available water in the root zone at the end of the season ($W_e = 0$; i.e., soil at permanent wilting point), then the value of the area ratio according to equation 4 drops to 3.5. Furthermore, it should be noticed that the area ratio, r , decreases at the same rate as the runoff coefficient, E_r , increases.

Farm Consumption Ratio

Three parameters are commonly used in the design and performance evaluation of RFWH systems: runoff coefficient, runoff storage ratio, and farm consumption ratio. The runoff coefficient was discussed in the previous section. The runoff storage ratio, E_s , is the ratio of the volume of runoff water stored in the root zone of the crop and the volume of the runoff collected in the catchment area. This ratio can be evaluated for each rainfall-runoff event. The factor that governs E_s is the deep percolation below the effective root zone depth of the cropped area. Without deep percolation, $E_s = 100$ percent. E_s was found to decrease with an increase in area ratio (r) for a given set of conditions. A higher runoff storage ratio is expected with larger root zone water-holding capacity, under drier conditions and with longer intervals between consecutive rainfall events (Oweis and Taimah 1996). Deep soils with high water retention capacity have a high runoff storage ratio.

The farm consumption ratio is defined as the ratio of the water stored in the root zone to the amount of rain received in the catchment area. Thus, the farm consumption ratio, E_o , is equal to the product of the runoff coefficient, E_r , and the storage ratio, E_s . The farm consumption ratio follows logically from the total water losses occurring in the catchment and the cropped area; a RFWH system with a relatively high runoff coefficient has a low farm consumption ratio if the runoff storage ratio, E_s , is low. Generally, the type of the soil and its depth play an important role in stabilizing crop production in RFWH systems. The best available engineering details for the design of RFWH systems are given by Critchley and Siegert (1991).

Supplemental Irrigation Water Harvesting

The second major type of rainwater harvesting system is a WH system with storage called supplemental irrigation water harvesting system. This system is highly recommended when inter-seasonal rainfall distribution, or variability, or both are such that crop water requirements cannot be met. In this case, the collected runoff is stored for later use as supplemental irrigation (Frasier 1994; Al-Labadi 1994). Surface storage facilities range from an on-farm pond or tank to a small dam constructed across the flow. Factors that should be considered in the design of such storage are:

1. Storage capacity, which depends on the available runoff volume, its distribution, and the pattern of water withdrawal from the storage (Frasier and Myers 1983).
2. Storage location, which depends on the topography, the value of the land, and whether withdrawal will be by gravity or pumping. Ideally, storage should be at the center of the farm to minimize the pumping and the conveyance costs for irrigation (Khanjani and Busch 1982). Under the most favorable circumstances, water will flow to all points of use entirely by gravity. On-farm storage ponds or dams are usually located on low quality or nonproductive land. Geographic Information Systems (GIS) can assist in siting farm ponds (see for instance, Vorhauer and Hamlett 1996; Tauer and Humborg 1992).
3. Type of storage, which can be any container capable of holding water depending on the availability of materials and labor. The soil at the site will affect the type and material of the tank. If the storage facility is to be located across a wadi or a gully, an earth-fill

dam may be selected. If the storage facility is located away from the runoff water source, a dug out or a ground tank may be used. In all cases, especially for dams built across streams and wadis, a safety provision, such as a spillway, is required to allow any excess water to bypass the storage (see figure 9).

4. Geometry of the storage tank, which depends on the topography. An important consideration is the volume-surface area relationship. A good dam site should provide the maximum storage capacity with the minimum surface area to reduce the loss of productive land and water by evaporation.

An off-stream storage must be built, if the construction of a dam in a wadi or a stream is not feasible, although this alternative is usually more expensive. An illustration of a possible layout of a catchment and a storage tank is given in figure 10. The cost of the storage facility and hence the cost of water depends on the ratio of the storage volume and the volume of the excavated earth, known as the storage/excavation (S/E) ratio (Hudson 1987). A S/E value of one, resulting when a hole is dug to store an equal volume of water, is the least economical value of this ratio. An obvious way to increase the ratio is by using the excavated soil to form a bank to contain the water above the original ground level. A natural depression may also be utilized and engineered to give a higher S/E ratio.

Construction specifications of tanks and reservoirs include allowable side slope, compaction requirements of dikes, free board heights, and spillway capacities. A reference is made to design handbooks for small dams. (USBR 1960).

FIGURE 9.
A small dam showing the spillway.

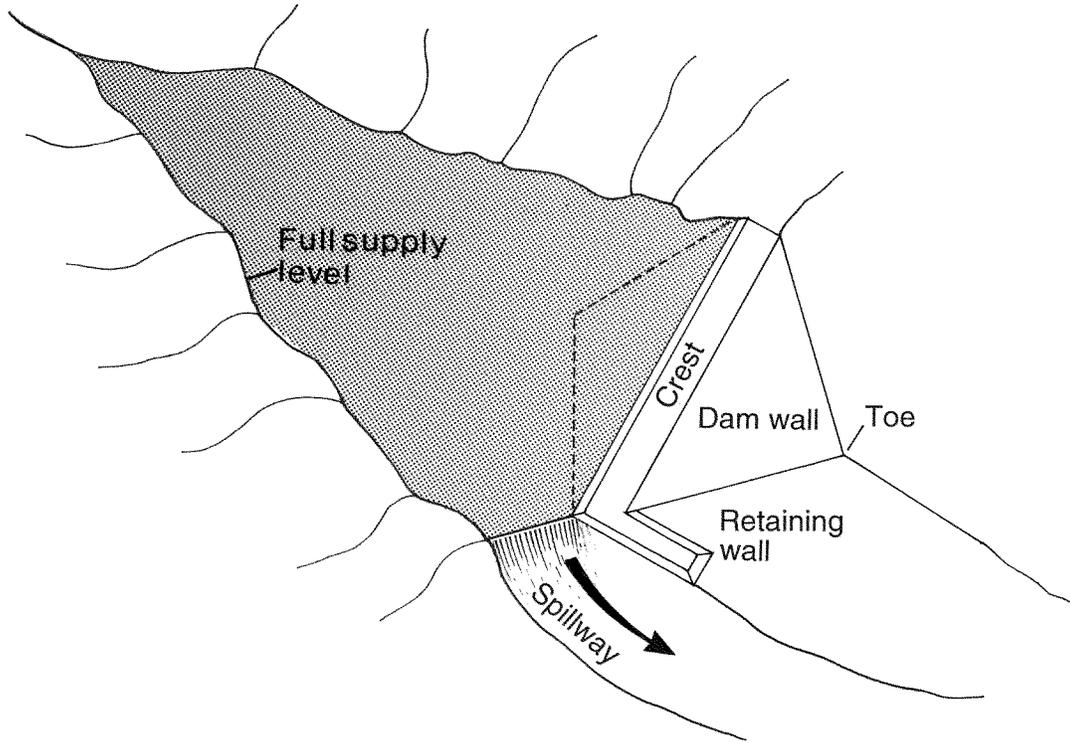
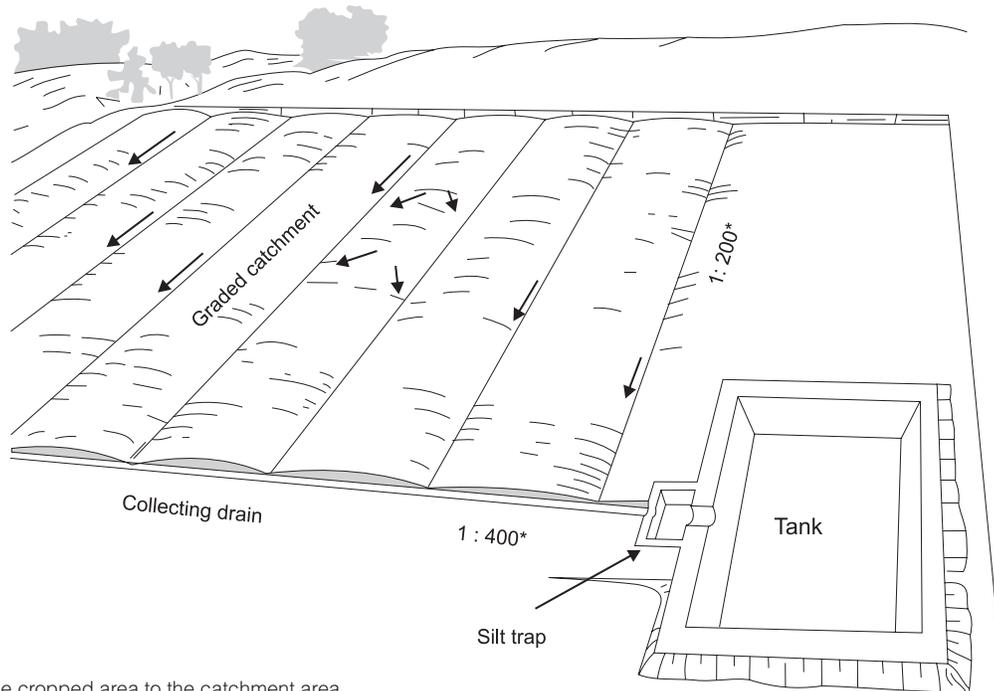


FIGURE 10.
Supplementary irrigation water harvesting system.



*The ratio of the cropped area to the catchment area.

Problems of Storage Facilities

Problems associated with storage tanks include excessive evaporation and seepage losses, and siltation. Limiting the surface area reduces evaporation losses. Floating covers and the application of surface layers have also been tried. Cluff (1981) reported the potential for evaporation reduction by the compartment tank method, in which the reservoir is divided into separate sections, allowing one section to be emptied into other sections when the stored volume is reduced, thus limiting the evaporative surface. Alternatively, the reservoir can be built with a sloping bottom. Seepage losses can be reduced by compaction and the application of lining materials. Siltation can be minimized by arresting the silt and sand on the catchment itself through erosion control, or by installing a silt-trap through which the runoff passes before it flows into the storage tank. The accumulated silt in the trap must be removed regularly, e.g., during the dry season.

Runoff Inducement

Runoff inducement is the practice of treating and sealing land surfaces to decrease infiltration and surface retention, and increase runoff. More often than not, WH systems exploit the presence of land with naturally low infiltration rates which is cheaper than treating soil surfaces artificially. These catchment areas are typically public lands, whereas the cropped area is privately owned by one or usually more farmers. Nevertheless, considerable research has been done on the methods and materials for the reduction of surface retention and infiltration of water (e.g., Emmerich, Frasier, and Fink 1987; Frasier, Dutt, and Fink 1987; Madramootoo and Norvile 1993; Fink and Ehrler 1981).

The various runoff-inducing surface treatments can be classified as follows:

1. Mechanical treatment: to clear sloping surfaces of vegetation and remove loose stones and materials to reduce interception of rain and obstruction of overland flow, permitting formation of a continuous surface crust under the energy impact of falling rain drops.
2. Smoothing and compacting the soil surface: to remove surface depressions and reduce soil permeability. Soil should be compacted at the right soil water content.
3. Reducing soil permeability: to apply chemicals to disperse the soil colloids by the application of chemicals.
4. Surface binding treatments: to permeate and seal the surface.
5. Application of a rigid surface: to cover the catchment with concrete, timber, or metal sheets. This method is prohibitively expensive but it has a long useful life expectancy (up to 20 years or more).
6. Application of a flexible surface: to cover the catchment with materials such as plastic, rubber, and fiberglass mat saturated with asphalt, which is also very expensive.

Of the various materials that bind and seal the soil surface, crude petroleum solution appear to be among the most feasible. This is universally available, water repellent, and able to bind loose soils. However, the presence of a high percentage of clay in the soil may cause cracks due to shrinking and swelling. Various additives may improve the weathering resistance and stability of the treated surface. Their application and dilution rates can be adjusted to achieve the desired soaking or penetration depth.

The high rates of runoff induced by such treatments may cause considerable soil erosion. It is therefore necessary to stabilize the surface

against erosion by water. To achieve this, the length of bare surface over which water is allowed to accumulate and run off must be carefully designed. Major channels that carry water must be grassed or lined to prevent scouring (Rose 1990).

Trampling by animals on catchments after surface sealing or coating treatments should be prevented, for example, by fencing, which however adds to the cost of a water-harvesting project.

The economic feasibility of surface treatment for inducing runoff needs to be assessed. It depends on the long-term costs of a unit volume of water compared with the value of the agricultural products. A comparison with the cost of water from alternative sources should be made. As a guide for the economic appraisal of WH systems, table 2 presents a comparison of various techniques for runoff inducement in terms of expected runoff and useful life (UNEP 1983).

TABLE 2:
Comparison of some of the techniques for runoff inducement.

Technique	Runoff (%)	Estimated useful life (years)
Land clearing	20–30	5–10
Soil smoothing	25–35	5–10
Sodium salts	40–70	3–5
Paraffin wax	60–90	5–8
Concrete	60–80	20
Membranes	70–80	10–20
Asphalt-fabric	85–95	15
Artificial rubber	90–100	15

Increasing Water Productivity through Supplemental Irrigation

The term *efficiency* is commonly used in discussing irrigation performance, but unfortunately, it leads to a great deal of confusion. *Efficiency* is generally understood to be a measure of the output obtainable from a given input. In irrigation and water management, typically the output is related to crop consumptive use and the input is the water diverted to meet crop consumptive demands (Israelsen 1950). Keller and Keller (1995) in referring to this as the *classical* definition of efficiency point out that it fails to take into consideration the fact that much of the water “lost” through runoff or seepage and

percolation is recycled or captured and reused elsewhere.

For the purposes of discussion, it is appropriate to avoid the confusion over the concept of *efficiency* and use the concept of *productivity*. *Efficiency* and *productivity* are related, but they are not the same. In measuring productivity, while the denominator remains the quantity of water diverted or depleted for a particular use such as crop production, the numerator is measured as the crop output. The numerator and the denominator can be expressed in either physical or monetary terms.

Given this, there are several different ways of expressing productivity (Perry 1996; Molden 1997).

- Pure physical productivity is defined as the quantity of the product divided by the quantity of the diversion or depletion.
- Combined physical and economic productivity is defined in terms of the economic value expressed as gross or net value, or net present value (NPV) divided by the amount of water diverted or depleted.
- Economic productivity is the NPV of the product divided by the NPV of the amount of water diverted or depleted, defined in terms of its value, or opportunity cost, in the highest alternative use.

In this discussion, we define water productivity (WP), using the first of the above definitions, as the ratio of the physical yield of a crop and the amount of water consumed, including both rainfall and supplemental irrigation. Yield is expressed as a mass (kg or ton), and the amount of water as a volume (m^3). After some introductory comments, three aspects of WP will be discussed in some detail: (i) crop-water-yield functions (also known as production functions), (ii) sensitivity of growth stages to water stress, and (iii) implications for timing of water application.

Crop varieties differ in their response to SI. Most wheat varieties in the dry areas have been developed either for resistance to drought under fully rain-fed conditions or for fully irrigated conditions. Some of the new and superior varieties can provide high yields only if water stress is eliminated and other factors such as soil fertility, aeration, salinity, and tillage are optimized. All management practices can thus influence the water productivity in SI. Crops have not yet been developed for a favorable response to the various levels and timings of SI. A proper selection of crop

varieties for the prevailing climate and management conditions could improve the yield levels and hence the feasibility of SI.

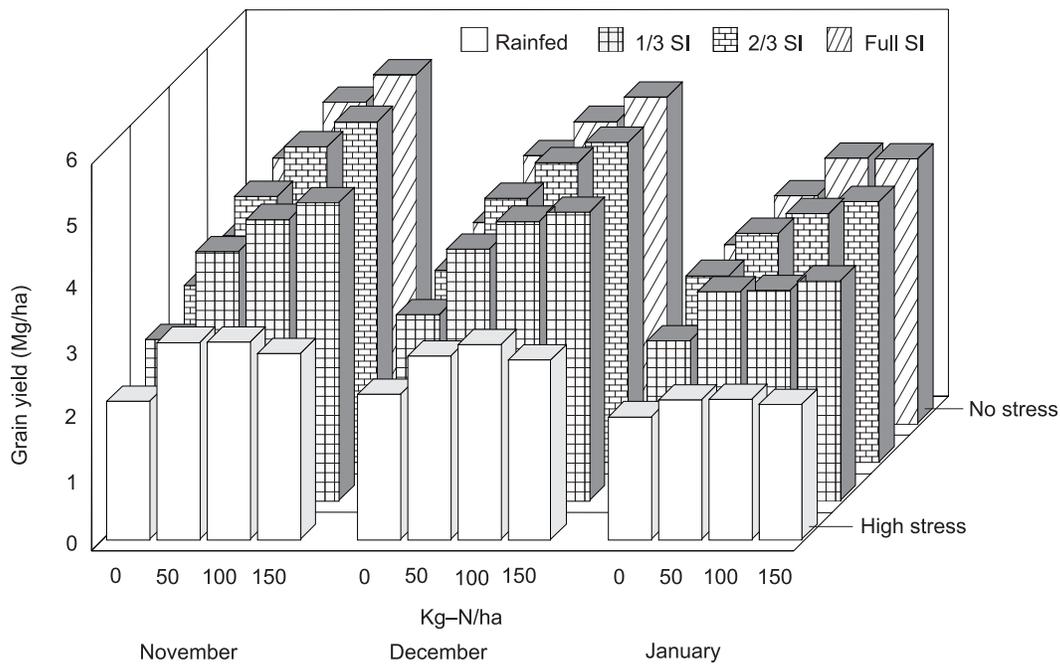
Work at ICARDA and in the demonstration plots on farmers' fields showed that with a SI of $1 m^3/ha$, the average yield of wheat was 2–3 kg/ha higher than under rain-fed conditions. In other words, the marginal WP was between $2 kg/m^3$ and $3 kg/m^3$. As expected, this value of the marginal WP compares favorably with the overall WP of full irrigation, which is of the order of $1 kg/m^3$ (Oweis 1997). The water productivity of rainfall in rain-fed wheat production at Mshaggar, Jordan, with 300 mm of annual rainfall was $0.33 kg/m^3$. The overall WP increased to $3 kg/m^3$, when the rainfall was supplemented by $0.5 m^3$ of SI. In the WANA region, the average WP of rainwater in wheat production is around $0.34 kg/m^3$, and for fully irrigated wheat $0.75 kg/m^3$, while under SI, average WP was estimated at $2.21 kg/m^3$ (Oweis 1997).

The effect on yield of a timely application of water under SI cannot be easily distinguished from the effect of improvements of other growth factors, such as fertilizer application and better plant material. Higher potential yields under SI justify higher inputs of other production factors. An example is the finding that the optimal response of wheat to a nitrogen fertilizer increased from 50 kg/ha under rain-fed conditions to 100 kg/ha under SI (Oweis, Zhang, and Pala 1998a; Oweis, Pala, and Ryan 1998b). An example of the between SI levels and the nitrogen fertilizer application is given in figure 11 (Oweis, Zhang, and Pala 1998a).

In rain-fed agriculture, planting dates are governed by the onset of rains, but with SI, it can be chosen precisely. An early sowing of wheat can improve WP significantly. For example, a delay in the sowing date of wheat in the Mediterranean countries from November to January consistently reduced the yield and the crop response to both SI and the nitrogen fertilizer (figure 11) (Oweis, Zhang, and Pala 1998a; Oweis, Pala, and Ryan 1998b;

FIGURE 11.

Wheat grain yields response to rainfall, levels of SI, and nitrogen fertilizer, and date of sowing in a Mediterranean-type climate.



Cooper et al. 1987). The selection of planting date plays an important role in reducing the amount and cost of SI water. However, there may be a trade-off between maximizing yield under SI and staggering planting dates in order to reduce the peak water demand and hence the required capacity and cost of the SI system. When the crop response to planting date is known, selecting the appropriate planting dates for the prevailing conditions can optimize both WP and irrigation system capacity. An analysis of the rainfall data can be used to facilitate the recommendations for improving SI design and management (Stewart 1991; Hargreaves and Samani 1989; Harris 1991).

Crop-Water-Yield Functions

The effects of the amount (and quality) of the applied water on crop production has been studied extensively. The response of crop yields

to applied water in the absence of salinity has been reviewed by Doorenbos and Kassam (1979) and Vaux and Pruitt (1983). Other recent reviews were conducted by Howell, Cuenca, and Solomon (1990), Fageria (1992), Joshi and Singh (1994), and Ragab (1996). The response of crop yield to soil salinity in the absence of water stress has been studied by Maas and Hoffman (1977) and Maas (1990). Data from yield-water relations and yield-soil salinity relations have been combined with models relating saline water application to soil salinity to construct water-salinity-production functions that relate crop yield to the volume and the salt content of the applied irrigation water. Examples of such combinations include the simulated crop production functions of Letey and Dinar (1986). A discussion of these various relationships, although of importance for crop production under supplemental irrigation in dry lands, is beyond the scope of this paper. References are made to the papers mentioned above and to Dinar et al. (1991) and Kijne (1998).

Crop-water-yield functions are often quite site-specific, as the dependence of crop yield on water application is affected by the timing of the water supplies, soil conditions, weather conditions, crop varieties, and agronomic practices. Substantial reductions in yield due to water stress at critical growth stages (e.g., anthesis and grain filling for grain crops) may occur although the total amount of water supplied during the growing season was adequate (Joshi and Singh 1994; Oweis, Pala, and Ryan 1998b). Evaporation from wet soil is probably the main component of the nonproductive water losses in dry areas. Rainfall distribution largely governs these losses. When seasonal rain comes mainly in small showers, evaporative losses are far greater than when the same amount of rain falls in a few heavy showers.

The structure of the soil surface, especially the presence of a surface crust, and soil fertility are the main soil-related factors affecting WP. In rain-fed agriculture, that a minimum amount of water must be available in the soil before the application of nitrogen fertilizer can be economically justified. Farmers mitigate the risk of applying the fertilizer that is later wasted when the crop fails due to water stress, by applying only a small amount (or none) at seeding. Additional fertilizer is applied at tillering.

Crop variety and species affect WP, as well as the agronomic practices, such as seeding rates and plant densities, weed and pest control. Drought-tolerant plants and varieties are often recommended for dry areas, but they are usually not the most efficient users of water (Tipton 88). Cultivars with a short growing season partially escape droughts, but during years with adequate rains they may yield less than the cultivars with longer growing season. The rapid establishment of a full ground cover minimizes water loss by evaporation from wet soil surfaces. Deeply rooted crops can benefit from water stored in deeper soil layers, but in areas with frequent light showers, a shallow and densely rooted crop is the more efficient water user (Gregory 1992). Depth of

seeding affects germination rates, as the seeds placed shallow may germinate too early if the rains fail to continue. Deep seeding on the other hand has the risk of forming a surface crust by the time the seeds try to emerge from the soil. In rain-fed agriculture, the date of the first significant rainfall determines the planting or the sowing date (Anderson and Dillon 1992; Harris 1991; Stewart 1991). Finally, the seed rate and the plant population density affect WP. When crops are mainly grown on stored soil water, rapid canopy development depletes available water early in the season. Thus, the crop may suffer severe water stress during later growth stages resulting in poor growth and low yields, as was reported by Tompkins, Fowler, and Wright (1991). Too low a plant density, on the other hand, would lead to low utilization of available soil water, as was found by Stewart and Steiner (1990).

Sensitivity of Growth Stages

Frequent mention has been made above of the differences in the sensitivity of crops to water stress during different growth stages. This growth stage effect was taken into account in the crop-water-yield function of Jensen (1968), who developed a function which divided the growing season into stages with evapotranspiration, ET, with each stage having a unique effect on the yield. Relative yield, i.e., the actual yield as a fraction of the maximum yield, is expressed as a function of relative ET, as follows:

$$Y/Y_{\max} = \text{SUM} (ET/ET_{\max})^b \quad (5)$$

where, ET_{\max} is the maximum seasonal evapotranspiration, which corresponds with the maximum yield, Y_{\max} , SUM is the summation over all growth stages, and b is the sensitivity index of the particular growth stage. As Vaux and Pruitt (1983) rightly commented, the accuracy of this model depends crucially on the accuracy of the sensitivity index, b .

The model of equation 5 does not allow for dependence of the effect of water stress on yield from one growth stage to another. This interstage dependence, however, is known to occur through the phenomenon of conditioning of a plant for water stress by subjecting it to stress during the early growth stages (Doorenbos and Kassam 1979). For example, the reduction in plant size by early stress appeared to harden a maize crop so that a deficit following the pollination period had less effect on the yield. Thus, interstage dependence cannot be treated separately from the issue of the timing of water applications. Interstage dependence can be accounted for if the terms for each of the growth stages are multiplied rather than adding the effects of the various growth stages, as was done by Jensen (1968). The accuracy of the sensitivity index remains of crucial importance (Ghahraman and Sepaskhah 1997).

Different independent variables have been used in crop-water-yield functions: applied water, soil water (either as water stress or soil water content), and ET. Relative evapotranspiration was used in the Jensen model, discussed above, but it is not a variable that can be measured easily and accurately. Soil water potential and soil water content can be measured in the field, but a large number of observations are needed to capture the large spatial and temporal variability of these parameters.

From the engineering and the economical point of view, applied water is a good choice as an independent variable, as it is the variable over which the irrigator exercises direct control. It may be argued that applied water is not the amount the farmer pays for if he is charged for the amount diverted from the source (irrigation canal, groundwater, or tank) (Vaux and Pruitt 1983). And neither is it the amount of water actually used by the crop. If applied water is used, the relation between yield and applied water is found to be curvilinear, contrary to the yield-transpiration or evapotranspiration relations which are usually linear. The yield-applied water curve

coincides with the yield-ET relation up to a point and then deviates from linearity with increasing water applications. This departure occurs because the irrigation efficiency decreases. The two lines would be identical as long as the irrigation efficiency is 100 percent. The departure from linearity is caused by deep percolation, runoff, and non-beneficial evapotranspiration losses.

Irrigation Scheduling

In water-scarce conditions, e.g., under SI of rain-fed agriculture, crops are often deliberately allowed to sustain some water stress and yield reduction. The aim is to increase water productivity by reducing the amount of water applied in irrigation or by reducing the number of irrigations. The term deficit irrigation has been coined for this practice. To do it successfully, farmers must know the deficit that can be allowed for at each of the growth stages, and the level of water stress that has already been in the root zone. The rule of thumb is that irrigation is needed when the soil water content drops to a depletion rate of 50 percent of available water (field capacity minus permanent wilting point) in the root zone for such crops as alfalfa, maize, and spring grains. Potato and vegetables may produce better when the soil water is maintained in the upper 35 percent of available water. To improve on this conventional bit of wisdom, one needs to know the crop-water-yield functions and the sensitive stages of the crops.

However, these production functions are not known with complete certainty, especially when the timing and the interstage dependency are important. Additionally, the crop-water-yield functions cannot be completely specified until the impact of other factors affecting production, such as fertilizer application, climate, water quality, and soil characteristics on the water-yield relationship are well understood (Vaux and Pruitt 1983).

Farmers are risk-averse and it has been found that they tend to select the cropping and water use patterns that are less profitable but more certain than the profit-maximizing combination. Hence, farmers tend to over-irrigate as a means of insuring against the penalties associated with water stress. In the absence of a more complete understanding of the yield response of various crops in different locales to alternate levels of soil water stress, the promise of water stressing as a means of economizing on scarce water supplies remains uncertain. As Vaux and Pruitt (1983) have pointed out, crops are often water stressed during droughts and in rain-fed agriculture in various regions of the world. The lessons of these experiences, however, are not readily transferable to most irrigated agriculture where cultural and management practices have evolved in the presence of adequate water supplies.

Varlev, Dimitrov, and Popova (1996, as quoted by Ragab 1996) discussed irrigation scheduling for maize on the basis of relative yield-relative ET relations, which were experimentally determined for different growth stages. The results showed that it was necessary to satisfy 75–80 percent of the crop water requirements starting from the most sensitive stages to the less sensitive stages. If relative ET was kept over 0.7, crop development would not be stressed during the following growth stage. It was found that, if two-thirds of the required water was available, yield levels of 90–95 percent of the maximum yield were attainable, compared with 40–50 percent under the rain-fed conditions of the semi-humid climate of Bulgaria.

Ragab (1996) has observed that irrigation scheduling under variable rainfall is usually developed to react to the actual rainfall received rather than to the predicted rain. The reason for this is that the actual date of the next irrigation can be adjusted according to the rainfall received between irrigations. This is particularly useful in semiarid regions with rainfalls that are highly variable in frequency and amount. It has been

attempted to apply less irrigation than would be required to refill the root zone to field capacity to reserve room for storage of rainfall shortly after the irrigation event, the so-called rainfall allowance. It may be suitable for deep rooted crops and soils with medium to high water holding capacities, but other than that, it is rather a risky business. During periods of peak ET, the rainfall allowances should be smaller to reduce the risk of crop failure due to water stress.

Simulation modeling has been used to develop water delivery schedules for SI in dry areas, taking into account crop-water-yield relations and rainfall probabilities. An example is the use of a model named ISAREG for summer irrigation of forage maize and supplemental irrigation of winter wheat in Mediterranean climates (Texeira, Fernando, and Pereira 1995). The model is based on the soil water balance approach proposed by Doorenbos and Kassam (1979). Daily computations of the water balance (equation 1) were made for a multi-layered soil with the option of additional water as a result of capillary rise from the water table. The model compared four irrigation scheduling options: maximum yield objective, supply restrictions during the peak month by adopting an allowable water deficit, an imposed rigid delivery schedule with either variable or preselected irrigation applications, and a negotiable delivery schedule. This last option uses a reiterative process to determine the optimal relative yield from the chosen irrigation depth, the water holding capacity of the soil, a yield-water production function, and an array of dates of the first irrigation. It was found that each of the four options of irrigation scheduling of forage maize in coarse textured soils can lead to water savings in spite of the small water holding capacity of the soils. With respect to SI of wheat on heavy soils in Tunisia, water can be saved by applying larger amounts of water in fewer irrigations than traditionally practiced. Probably, the most important conclusion is that under water-stress conditions, irrigation scheduling can be improved using simulation models.

In actual practice, it is necessary that the infrastructural arrangements of the irrigation system be such that water can be reliably delivered according to a flexible, on-demand type, schedule. In many of the irrigation systems intended for full irrigation, this condition is not satisfied and water is delivered according to a rigid, rotational schedule. Recent studies indicate that a fixed schedule, if executed correctly and reliably, has only a small disadvantage in yield potential compared with a variable one, while the infrastructural requirements and management demands are less (e.g., Bhirud, Tyagi, and Jaiswal 1990; Perry 1993). This structural and managerial drawback of flexible water delivery systems is probably insignificant in the type of SI systems discussed herein.

Other Issues and Experiences in SI Management

In this paper, we have looked mainly at the water harvesting and supplemental irrigation techniques in developing countries, especially in the WANA region. The SI techniques in the USA are also noteworthy. Among the pioneering studies on SI carried out during the 1970s and 1980s are those of Stewart and coworkers in the U.S. Great Plains regions (Stewart, Dusek, and Musick 1981; Stewart and Musick 1982; Stewart 1989). In their work, the terms "limited irrigation" and "conjunctive water use" were used interchangeably with supplemental irrigation to describe the technique of farmers cultivating sorghum and cotton in the Texas High Plains, who drilled wells to irrigate their rain-fed crops. Increased yields associated with low-cost, high-productivity inputs resulted in a large increase in the number of irrigation wells and changed local practice from supplemental to full irrigation, thus maximizing the yield per unit land. Later, however, as Stewart and Musick (1982) pointed out, declining groundwater supplies and increasing cost of energy caused a shift back to SI and later to rain-fed farming practices.

From this 50-year large-scale example, involving a transition from fully rain-fed to fully irrigated and then back to supplemental irrigation, the following lessons can be learned:

1. The cost and the presence of sustainable water supply are the major factors in the development of SI.
2. With adequate water supplies, water is generally applied in sufficient amounts to achieve maximum yield per unit area.
3. With limited water supplies, the question arises whether a given amount of water can be utilized more efficiently by supplying a small area with the full requirement or by supplying a larger area with less than the full requirement (i.e., deficit irrigation). This is really a matter of economics. When a new land is being developed, meeting the full water demand is often economical, but in areas with existing irrigation systems and declining water supplies, such as the Great Plains, SI may be more feasible. However, in the benefit-cost analysis, the management systems for SI should be carefully planned and costed to ensure that the gains in crop yield due to higher WP are not offset by increased costs of tillage, seeding, fertilization, pest control, and harvesting.
4. Many deficit-irrigation systems have been proposed for the efficient use of limited supplies of irrigation water. Among those that may hold promise for the dry areas of WANA region is the irrigation of alternate furrows with either a constant or a variable seeding rate along the ridges between the furrows. Furrows not used for irrigation are dammed, and there is at least one dammed furrow between two irrigated ones.

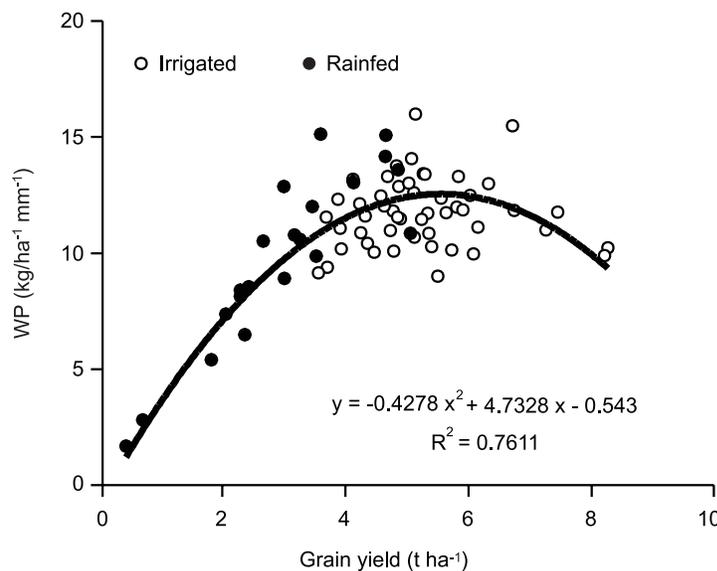
It has been suggested that different levels of SI (i.e., intentional deficits) can be simulated to

obtain SI requirements for different yield levels. To calculate the economic feasibility of these various SI levels, a reliable yield-water relation is needed. In practice, attempting to define these levels accurately has often been found impossible due to uncertainty in the data and the estimated costs and benefits (Hachum and Rasheed 1987). With respect to deficit irrigation, it has been argued that in the absence of reliable and accurate planning tools, the best practice for farmers is to try to meet the crop water requirements. In the open field, little can be done to decrease evaporation if the conditions for high yields are to be maintained. As Hillel (1990) has remarked, it appears that the greatest promise for increasing WP lies in allowing the crop to transpire freely at the climatic limit. This can be achieved by alleviating any water shortages, while at the same time controlling all other processes of water loss and obviating the other environmental constraints to attain the full productive potential of the crop.

Water productivity data for wheat in Syria is plotted against grain yield, expressed as yield per unit land in figure 12 (Oweis, Zhang, and Pala 1998a). The highest value of WP was about 1.5 kg/m³. It is noteworthy that the highest WP has been achieved at the cost of lower yield per unit land. This finding has important implications for the management of SI; it confirms the need to optimize water use in terms of yield per unit water to achieve high WP in water-scarce conditions.

Sprinkler irrigation is considered to be the most suitable method for SI. As Hachum and Yasin (1992) and Keller and Bliesner (1990) have indicated, sprinkler irrigation equipment is capable of supplying small amounts of water with a high degree of uniformity, causing little or no erosion, nor deep percolation. Fertilizers and agro-chemicals can be mixed in the water. And, sprinkler irrigation can cover irregular terrain with different types of soil and crops, especially when the equipment is portable.

FIGURE 12.
Yield relation for durum wheat in Syria.



Socioeconomic and Environmental Aspects of Water Harvesting and Supplemental Irrigation Systems

Many water harvesting and supplemental irrigation systems have failed, despite good techniques and design, because the social, economic, and management factors were inadequately integrated into the development of the system (Bazza and Tayaa 1994). In other cases, where efforts have been made to introduce WH or SI technologies, the sustainability (e.g., impact on water tables) and environmental impacts have been overlooked.

Socioeconomic Considerations

One condition for the success of WH and SI techniques is the acceptance by the resource users (male and female farmers). The chances for success are much greater if they are involved from the early planning stages onwards. However, the risk levels and profit potential for investment of labor and other inputs must also be acceptable. There are few studies that have assessed the economics of WH and SI.

To the extent possible, the introduction of WH and SI techniques should build on the existing indigenous water conservation measures. Most WH techniques are quite simple and can be understood by the farmers. SI tends to require more sophisticated management. It is often, and quite wrongly assumed that the beneficiaries will understand the priorities, participate effectively, and organize themselves for operation and maintenance of the system without explanation or training. As Critchley and Siegert (1991) put it:

It is sad but true that very often the people simply do not understand what a project is trying to achieve, or even what the meaning of the various structures is!

Thus, the benefits of the project should be apparent to the farmers as early as possible. Motivation and promotion of awareness among the people with regard to the project objectives and the ways to achieve them are essential. The water harvesting techniques typically require commitment and cooperation of a group of neighboring farmers in the construction, operation, and maintenance of facilities, to coordinate and control the use of the catchment, cropping areas, and the bunding structures. The transaction costs for achieving this commitment and cooperation can be very high. Most WH techniques are most effective at a larger scale than the individual farms in countries where landholdings are small. For example, in western Rajasthan, the submerged area behind the traditional bunds (khadins) range from 20 hectares to as much as 500 hectares.

Kolavalli and Whitaker (1996) have observed in Rajasthan, India, that today local communities seldom initiate group action to develop new WH structures. Community efforts nowadays involve considerable assistance from external agents, such as nongovernmental organizations. They concluded that the lack of developed local institutions is a critical constraint to exploit the potential of WH. A corollary is that in the last 20 to 30 years, the responsibility for the maintenance of bunds in western Rajasthan has gradually been taken over by the Irrigation Department (ID). In the larger WH systems, the ID has constructed reliable overflow structures in the bunds to reduce the pressure on the bund when rains are heavy. These overflow structures lessen the need for regular maintenance, so that now regular maintenance is no longer being done by either the farmers or the ID (Kolavalli and Whitaker 1996).

An obvious condition for success is the economic feasibility in both initial construction

and maintenance costs. Acceptance by the local community and the economic viability of WH and SI systems are improved when WH and SI are not considered as a free-standing technique, but as part of a village or regional land use management plan. At the establishment of a WH or SI system, agronomic practices, such as weeding, fertility management (e.g., application of compost and farmyard manure), pest and disease control, etc. should also be improved. Multiple planting to increase rainfall utilization should become a standard practice under WH. For SI, the knowledge of water-stress sensitive growth stages in relation to the timing of water application is critical. It is obvious from these examples that WH and SI should be part of an integrated land use improvement package, for which farmers need to be trained (Rey 1992, personal communication).

Understanding the specific needs of a local community or a group of beneficiaries is therefore critical in designing and implementing an appropriate system. To enhance the sense of ownership by the local community, involving the beneficiaries in carrying out such tasks as keeping rainfall and runoff records has been found to be successful. Further participatory activities are in maintenance and in evaluation. Possible modifications could be made to the system after some time.

Studies conducted in India show that acceptance of a new technology depends on farmers' attitudes toward production risk and their perceptions of the risk. It is often important to know whether differences in adoption behavior among farmers are caused by the differences in their perception about the risks involved in a new technique, or by the differences in the constraints they face in accessing credit and other inputs (Binswanger 1980). Risk-averse farmers can be expected to accept a new technology if they perceive that the increased risk is compensated by the increased returns. When the risk was expressed as the standard deviation in net returns, farmers accepted the new technology

when they perceived that the increased risk was less than double the increased mean net return. It is important to study farmers' acceptance of WH and SI technology in these terms to quantify likelihood of acceptance, which may be helpful in developing appropriate investment strategies for WH and SI techniques in these marginal lands.

Local people should decide on the organization of WH system construction and prioritize the setting of the fields to be treated. However, to prevent greater inequality at the village level as a result of the introduction of WH, special care should be taken to make sure that poor farmers and woman farmers have equal access to the technique. Attention should be given in this context to the interaction between WH and land tenure.

It may be appropriate in some situations to provide incentives and support to farmers for the implementation of WH and SI systems. Examples of such incentives range from gifting tools, plows, donkey carts, etc. to providing food for work. Rey (1992) has argued convincingly that the type of incentive and support should be defined in close consultation with the local resource users, in order to improve the chances for post-project expansion and proper maintenance of the system. It should be attempted to nationally coordinate the incentive systems for various WH and SI initiatives. In the absence of coordination, farmers in one system may receive far less for their labor contribution than others working nearby in a differently funded project, which could lead to (covert) obstruction of the activity.

Generally, it is important to know more about the reasons for adoption or refusal of WH and SI techniques by local communities. This applies specifically to the choice between using local labor and heavy machinery with its attendant capital costs.

Environmental Issues

Dry area ecosystems are generally fragile and have a limited capacity to adjust to change. If the

use of the natural resources, especially land and water, is suddenly changed, for example, by the introduction of WH or SI systems, the environmental consequences are often far greater than foreseen. It has been observed that the application of intensive agricultural practices to dry areas may result in:

1. Rising water tables and waterlogging in the absence of adequate subsurface drainage, or lowering of water tables because of over-exploitation of the groundwater resource. In dry areas, the latter is more likely than the former and often results from the introduction of SI.
2. Salinization (accumulation of soluble salts in the soil) and sodication (increase in the exchangeable sodium content in the soil) thus degrading the land and reducing the productivity (Kijne et al. 1998). This is often the result of deficit irrigation when not enough water is applied, either as SI or rainfall, to maintain a favorable salt balance in the root zone of the crops.
3. Soil degradation due to poor soil surface management and accelerated soil erosion on marginal lands.
4. Contamination of surface water and groundwater sources by fertilizers and pesticides (Lal, Eckert, and Logan 1990).
5. Creation of vector habitats and the increased incidence of diseases following the construction of surface water reservoirs in hot climates (Carter, Brook, and Jewsbury 1990).

Several of these adverse effects may occur because of the introduction of WH and SI in fragile dry areas. The introduction of new WH and SI systems should take cognizance of these risks during the planning stage. Also, at this time, consideration should be given to the possible

effect on other water users, both in terms of water quantity and quality. New WH systems may intercept runoff at the upstream part of the catchment, thus depriving potential downstream users of their share of the resource. An example is the wadi bed system in the Matruh area in northwest Egypt, where the introduction of WH techniques negatively affected water users in the past in the downstream part of the system (Moustafa 1994). The notion that WH uses hydrologically insignificant amounts of water should not be accepted without proof.

The necessary conditions for adoption of the new technologies, e.g., WH and SI, are often—at least to some extent—location-specific as they are influenced by cultural differences, level of education, and awareness of the need for change among the beneficiaries. It has been found that land and water resource users are usually aware of land degradation but they may not have a choice when it is a question of survival. They are unlikely to quickly adopt new practices unless they are convinced that adoption is financially advantageous, and the new practices do not conflict with other activities they consider important or demand too much of their time for maintenance (Gallacher 1994). Also, measures that require collaboration with more people than they are used to, for example, for the conservation of upper slopes, or for the treatment of common catchment areas and runoff zones, are unlikely to be readily accepted.

As has been argued, WH technology should be seen as one component of a larger village level or regional water management improvement project. Components of such integrated plans should be the improvement of agronomic practices, including the use of good plant material, plant protection measures, and soil fertility management. Another condition for the successful introduction of WH and SI techniques is institutional capacity building for the development of appropriate water resources investment programs, water resource management policies, and management and

maintenance programs of WH and SI systems. The institutions whose capacity need to be strengthened could be at the village, regional,

and national levels depending on the size of the WH and SI projects and the degree of decentralization in the country concerned.

Recommendations and Research Needs

Recommendations

The following recommendations are not new or original, but they largely repeat what has been said before in other publications. Nevertheless, they deserve to be repeated here for the successful introduction of new WH and SI systems and for greater water productivity in the existing agricultural production systems become more pressing. The following are a few recommendations:

- To facilitate the transfer of information on various designs of WH systems, the data and the information related to the designs of all WH systems should be collected in a database in the public domain.
- National institutional arrangements should be made to coordinate the design and implementation of various WH projects within a country, and to build a database to record the experience.
- In many countries, there is a need to systematically collect and collate (e.g., through geo-information systems) data on soils, natural vegetation, cropping patterns, rainfall amounts, intensity and probability, water resources, and crop water requirements as part of a national inventory of the potential WH and SI sites.
- The planning of WH systems should be a part of an integrated land and water resource management plan, and should include the improvement of agronomic practices and farmer training.
- Local resource users should be involved in all aspects of the planning and implementation of WH and SI systems. Planning should consider explicitly the effect on downstream water users of the hydrological changes brought about by the implementation of WH and SI. Opportunities for equal access of women and other disadvantaged farmers to the benefits of the new technology should be provided; and the relation between land tenure, water rights, and the introduced technologies should be carefully considered.
- The planning of WH systems should include the careful consideration—in collaboration with the resource users—of whether the WH system can be constructed by local labor, provided appropriate incentives and compensation are offered, or whether the use of heavy machinery is necessary and appropriate.
- Performance assessment of WH and SI systems should be carried out according to a common format to facilitate comparison between various systems. This should include the data and information on the size and the type of WH system, crops grown and yield levels, annual rainfall, amount of runoff collected per unit catchment area, socioeconomic impacts, and social acceptance.

- There is a need to emulate WH techniques developed at experimental stations on a larger scale of a field situation to assess their viability and effect on agricultural productivity.

Research Needs

No attempt is made to make an exhaustive list of the research needs. It merely brings together some suggestions to strengthen the studies mentioned in this paper. Existing studies on physical relationships should be complemented by studies on economic and policy implications of investments in the rural development of marginal lands. Studies are needed:

- On the necessary conditions for the successful introduction and interregional transfer of specific WH and SI techniques to anticipate the likely constraints on adoption of the new technologies, including those arising from land tenure and water rights issues, risk factors, and potential economic benefits.
- On the extent to which traditional water harvesting systems can be used as a starting point for the new WH systems, and to evaluate the possibilities for optimizing water

use efficiency (Critchley, Rey, and Seznec 1992).

- For the development of crops and crop species that produce well under conditions of limited water supply characteristic of WH and SI systems in dry lands.
- On the hydrological behavior of small catchments and the development of simple and reliable methods for estimating runoff efficiency under a wide range of physical conditions and for variously sized catchments.
- On appropriate investment policies in harsh environments, where local populations are barely able to subsist without infrastructural interventions. These studies should assess the likely benefits in terms of economic, social, and environmental effects resulting from such investments (see I. Serageldin in Forward of Critchley, Rey, and Seznec 1992).

And finally, studies that critically evaluate the experiences with the implementation of WH systems with heavy machinery and the mobilization of people through the systematic use of food for work programs (I. Serageldin *ibid.*) are needed.

Case Study 1

The Amamra project area comprises 16,000 hectares and is located on the Mediterranean coast 22 km southwest of Homs, 120 km east of Tripoli in northwest Libya. The average annual rainfall is 348 mm, and falls between September and April. The coefficient of variation is high. The project area is mostly hilly with small valleys and scattered depressions. The soils are light textured, especially near the surface.

The project objectives were to control erosion resulting from high intensity showers on the fragile soils of the hills; to construct contour-ridge terraces to conserve water for soil storage and use by tree crops near the collection ditches above the contour ridges, and barley in the inter-ridge area; to establish 292 farms ranging in size from 27 hectares to 40 hectares according to the production potential; to select 292 families and their settlement on these farms to live on mixed production of tree and grain crops and sheep production; and to introduce training and extension programs to replace the nomadic habits of the farmers by modern farming techniques.

The basic design concept was to allow the collected runoff water behind the ridges to infiltrate the soil surface and be stored in the soil profile to meet the dry season water requirements of fruit trees planted along the collection channels. At the same time, the retardation of runoff water velocity across the space between ridges was expected to increase the infiltration opportunity time and to provide enough water for grain crops to achieve reasonable yields. The information gained after 20 years of operation, however, does not confirm these assumptions.

The project was executed in 1973 by the local and international contractors. For the construction work, heavy machinery and foreign

labor were used without involving the intended beneficiaries.

Almost all of the people selected for resettlement on the project farms were uneducated and lacked the capacity to understand and absorb the technical information and skills considered necessary for the successful operation and management of their farms. Most of them were not inclined to accept the new technology. They reluctantly accepted the project in the hope that it would bring them other highly desirable services such as electricity, housing, schools, hospitals, and community centers. Thus, it was clear from the beginning that attention must be paid to train the would-be farmers. But this important issue was neglected and delayed until the completion stages.

Another problem that was not properly considered during the planning and construction stages was land tenure and legal property rights. Most of the reclaimed land is considered the communal property of the local tribes and, when divided among families or individuals, the Islamic laws of inheritance are strictly applied. A limited number of 292 families was selected from a larger number of local people. The remaining people had to be relocated outside the project boundaries or they had to serve in other nonfarming activities within the project. But those non-beneficiaries insisted on remaining on their share of land, to which they are entitled by the Islamic law and the tribal customs. This problem had been complicated by the inability of the official authorities either to provide acceptable areas for relocation of the non-beneficiaries, or to create other nonfarming activities and suitable jobs for them. Thus, the water harvesting control systems were neglected; the fruit trees not looked after properly, farm incomes declined

sharply, and the settlers began to look for other opportunities to support their families.

The selected hydraulic system of water control and redistribution is generally effective in controlling soil erosion and conserving rainfall runoff for increased agricultural production. Consequently, at least some of the project objectives have been partly achieved. The

inability of the project to achieve its full potential has been largely due to constraints imposed by the socioeconomic problems which had not been properly solved at the planning stage. The most important problem is related to land tenure and property rights.

Saad A. Alghariani 1994

Case Study 2

Dier-Atye in Syria was selected for the development of a water harvesting project because the area is covered with a dense network of gullies and wadis indicating that the rainfall and topography naturally induce large amount of runoff. The area is representative of the region of the Kalamoun mountains where a large-scale application of positive results from the project would be possible. Annual rainfall is about 120 mm, and limited to 7 months from October to April, typical for most parts of the Syrian steppes. The area is promising for the development of fruit trees and rangeland, and the community of Deir-Atye is very interested in agricultural development, which is demonstrated by large tree plantations in the vicinity of the village. The villagers are also interested in new methods of saving irrigation water for the horticultural and fodder crops, and were willing to support the pilot station by the contribution of machines for the execution of works. The village community is closely knit and the village was the site of the first agricultural cooperative in the Arab world, which was established in 1941.

To design the trials and obtain the required data, a committee was formed comprising representatives of the Soils Division, Water Division, and the Plant Division of the Ministry of Agriculture, and of GTZ, the German Organization for Technical Cooperation. The

committee decided on the location of the project area of 130 hectares, the division of the land in 4 parts (for fruit trees, range plants, cereals, especially barley, and for experiments on runoff). The committee adopted the micro-catchment method of collecting rainwater around the trees, except for *Pistacia Atlantica* (Pistachio) which was planted in rows on the contour lines, the contour planting for range crops with specified distances between the rows of plants, the planting of barley in a limited area, and constructing a net of small canals to collect the runoff water for distribution to the planted area.

The chosen WH system was contour lines with small embankments and basins for planting of range plants and contour plowing for the seeding of range plants. The contour lines were dug by the ripper of a dozer; the embankments and plantation basins were formed by hand along contours at 1 m vertical spacing. For the field crop area, the runoff area has dikes in a fishbone pattern to convey the runoff to a natural gully and from there to a retention dam. The water is guided to the top of a plowed and sown field of barley by pipes.

The micro-catchment method proved its potential for WH in arid and semiarid zones for fruit tree plantations. Runoff, twice yearly at least, satisfies the water requirements of the chosen species, almond, pistachios, fig, grape, and other

species adapted to the environmental conditions. The range plants may be sown or planted on contour lines with embankments of at least 30 cm high. If the contour line soil is ripped, the range plants will receive sufficient runoff water to satisfy the requirements.

Water harvesting was not economical for field crops in mountainous areas because, the

techniques required are expensive and the plants do not receive equal quantities of runoff water. Also, as the rainstorms are not regular, there is a high risk that crop seeds will not germinate if the rains occur late.

Ibrahim Haj Ibrahim 1994

Case Study 3

Until the early 1980s, most soil and water conservation projects in Burkina Faso had failed dramatically. From 1962–1965, heavy machinery was used to treat entire catchments in the Yatenga region of Burkina Faso's Central Plateau with earthen bunds. Although the project, which treated 120,000 hectares in 2.5 dry seasons was technically well conceived, the land users were not involved, and they were not at all interested in maintaining what had been constructed. From 1972–1986, several donor agencies funded a soil and water conservation project based on a more "participatory approach." Earth bunds were constructed on plots of 30–60 hectares, but in this case, the land users were not willing to maintain the earth bunds for various reasons (high maintenance requirements, lack of benefits, etc.) and most bunds were severely degraded or had entirely disappeared after 3-5 years.

The Oxfam²-funded Agro-forestry Project (1979–1981) in the Yatenga region tested a number of simple soil and water conservation/ water harvesting techniques and asked the villagers to evaluate the techniques. They showed a preference for contour stone bunds, which in fact was an improvement over the traditional stone lines that can be found in various parts of the Central Plateau. Better

construction of the stone lines (on the contour, level bunds, etc.) considerably improved the technical efficiency of the stone lines. The Agro-forestry Project also devised an extension strategy, which focused on training the farmers at village level in the use of a water tube level, enabling them to determine contour lines themselves. The number of hectares treated by farmers with contour stone bunds increased rapidly from 7 hectares in 1981 to an estimated 600 hectares in 1985. In the Yatenga and other parts of the Central Plateau, tens of thousands of hectares have now been treated with contour stone bunds. It is impossible to estimate this number accurately, because not only many projects are actively promoting the construction of contour stone bunds, but also many farmers are treating their fields on their own initiative without any external support. Although villagers collectively treat village farm fields, most of them also treat their "bush fields" on an individual basis.

At the end of the 1970s, a farmer in a village near Ouahigouya, the capital of the Yatenga region, experimented with traditional planting pits. He increased their dimensions and added some manure to the pits. In this way, water and fertilizers were concentrated on the same spot.

²Oxfam is a British charity nongovernment organisation.

These so-called zay (diameter 0.2–0.3 m; depth 0.15–0.3 m and spacing 0.8–1 m) were used, often in combination with contour stone bunds, to rehabilitate barren and strongly degraded land. Particularly in the Yatenga region, these improved zay were rapidly adopted by many farmers.

The main reason why farmers spontaneously adopt contour stone bunds and improved

traditional planting pits is that they produce immediate and substantial yield increases. On a land that is already cultivated, the construction of contour stone bunds is estimated to increase yields by 40 percent.

Johan van Dijk and Chris Reij 1994.

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