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The Role of Water Harvesting and Supplemental Irrigation in Coping with Water Scarcity and Drought in the Dry Areas

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I. INTRODUCTION

Water scarcity and drought are among the most serious obstacles to agricultural development and a major threat to the environment in the dry areas. Agriculture in the dry areas accounts for more than 75% of the total consumption of water. With rapid increases in demand, water will be increasingly reallocated away from agriculture and the environment.

Despite scarcity, water continues to be misused. Mining groundwater is now a common practice, risking both water reserves and quality. Land degradation is another challenge in the dry areas, closely associated with drought-related water shortage. Climatic variation and change, mainly as a result of human activities, are leading to depletion of the vegetation cover and loss of biophysical and economic productivity. This happens through exposure of the soil surface to wind and water erosion and shifting sands, salinization of land, and water logging. Although these are global problems, they are especially severe in the dry areas.

Two major environments occupy the dry areas. The first is the wetter rain-fed areas, where rainfall is sufficient to support economical dry farming. However, because rainfall amounts and distribution are suboptimal, drought periods often occur during one or more stages of crop growth, causing very low crop yields. Variation in rainfall amounts and distribution from one year to the next causes substantial fluctuations in production. This situation creates instability and negative socioeconomic impacts. The second environment is the drier environment (steppe or *badia*), characterized by an annual rainfall too low to support economical dry farming. Most of the dry areas lie in this zone. Small and scattered rainstorms in these regions fall on lands that are generally degraded with poor vegetative cover. Rainfall, although low, may accumulate through runoff from vast areas in a large volume of ephemeral water and largely be lost through direct evaporation or in salt sinks.

With scarcity, it is essential that available water be used at highest efficiency. Many technologies are available to improve water productivity and management of scarce water resources. Among the most promising technologies are (1) supplemental irrigation (SI) for rain-fed areas and (2) rainwater harvesting (WH) for the drier environments (Oweis and Hachum, 2003). Improving scarce water productivity, however, requires exploiting not only water management but also other inputs and cultural practices. This chapter addresses the concepts and potential roles of supplemental irrigation and water harvesting in improving water productivity and coping with increased scarcity and drought in the dry areas.

II. SUPPLEMENTAL IRRIGATION

Precipitation in the rain-fed areas is low in amount and suboptimal in distribution, with great year-to-year fluctuation. In a Mediterranean climate, rainfall occurs mainly during the winter months. Crops must rely on stored soil moisture when they grow rapidly in the spring. In the wet months, stored water is ample, plants sown at the beginning of the season are in early growth stages, and the water extraction rate from the root zone is limited. Usually little or no moisture stress occurs during this period (Figure 1). However, during spring, plants grow faster, with a high evapotranspiration rate and rapid soil moisture depletion due to higher evaporative demand. Thus, a stage of increasing moisture stress starts in the spring and continues until the end of the season. As a result, rain-fed crop growth is poor and yield is low. The mean grain yield of rain-fed wheat in the dry areas is about 1 t/ha, far below the yield potential of wheat (more than 5–6 t/ha).

Supplemental irrigation aims to overcome the effects of drought periods as soil moisture drops and halts crop growth and development. Limited amounts of water, if applied during critical times, can result in substantial increases in yield and water productivity.

Research results from the International Center of Agricultural Research in the Dry Areas (ICARDA) and other organizations, as well as harvests from farmers' fields, have

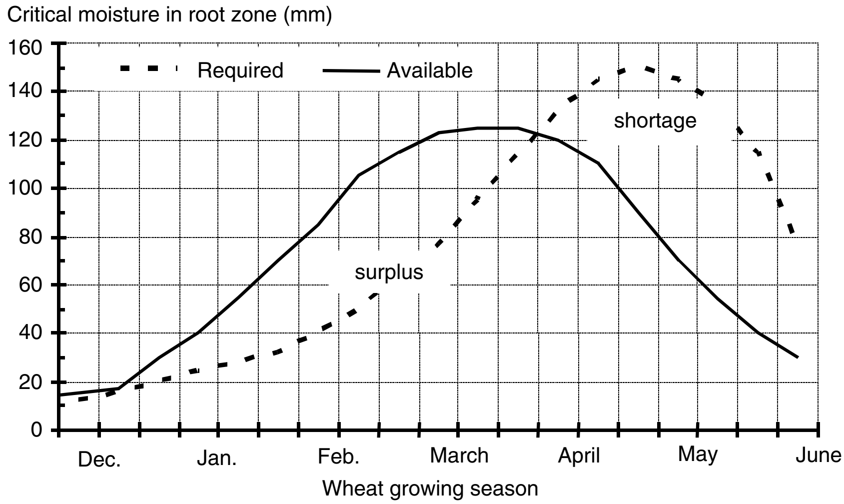

Figure 1 Typical soil moisture pattern over the growing season of a Mediterranean-type wheat. (From Oweis, 1997.)

demonstrated substantial increases in crop yield in response to the application of relatively small amounts of irrigation water. Table 1 shows increases in wheat grain yields under low, average, and high rainfall in northern Syria, with application of limited amounts of SI. By definition, rainfall is the major source of water for crop growth and production; thus the amount of water added by SI cannot by itself support economical crop production. In addition to yield increases, SI also stabilized wheat production over years (i.e., reduced the interannual variability of yields).

The impact of SI goes beyond yield increase to substantially improving water productivity. The productivity of irrigation water and rainwater is improved when they are used conjunctively (Oweis et al., 1998, 2000). Average rainwater productivity of wheat ranges from 0.35 to 1.0 kg/m^3. It was found that 1 m^3 of water applied as SI at the proper time could produce more than 2.0 kg of wheat.

Using irrigation water conjunctively with rain was found to produce more wheat per unit of water than if used alone in fully irrigated areas where rainfall is negligible. In fully irrigated areas, water productivity for wheat ranges from 0.5 to

TABLE 1 Yield and Water Productivity (WP) for Wheat under Rain fed and Supplemental Irrigation (SI) in Dry, Average, and Wet Seasons in Tel Hadya, North Syria

Season/Annual Rainfall (mm)	Rainfed Yield (t/ha)	Rainfall WP (kg/m^3)	Irrigation Amount (mm)	Total Yield (t/ha)	Yield Increase due to SI (t/ha)	Irrigation WP (kg/m^3)
Dry (234 mm)	0.74	0.32	212	3.38	3.10	1.46
Average (316 mm)	2.30	0.73	150	5.60	3.30	2.20
Wet (504 mm)	5.00	0.99	75	6.44	1.44	1.92

Source: Adapted from Oweis (1997).

about 0.75 kg/m^3, one-third of that achieved with SI. This difference suggests that allocation of limited water resources should be shifted to more efficient practices (Oweis, 1997). Food legumes, which are important for providing low-cost protein for people of low income and for improving soil fertility, have shown similar responses to SI in terms of yield and water productivity.

In the highlands of the temperate dry areas in the Northern Hemisphere, frost occurs between December and March. Field crops go into dormancy during this period. In most years, the first rainfall sufficient to germinate seeds comes late, resulting in a poor crop stand when the crop goes into dormancy. Rain-fed yields can be significantly increased if the crop achieves good early growth before dormancy. This can be achieved by early sowing with application of a small amount of SI. A 4-year trial, conducted at the central Anatolia plateau of Turkey, showed that applying 50 mm of SI to wheat sown early increased grain yield by more than 60%, adding more than 2 t/ha to the average rain-fed yield of 3.2 t/ha (ICARDA, 2003). Water productivity reached 5.25 kg grain/m^3 of consumed water, with an average of 4.4 kg/m^3. These are extraordinary values for water productivity with regard to the irrigation of wheat.

A. Optimization of Supplemental Irrigation

Optimal SI in rain-fed areas is based on the following three criteria: (1) water is applied to a rain-fed crop that would normally produce some yield without irrigation; (2) because rainfall is the principal source of water for rain-fed crops, SI is applied only when rainfall fails to provide essential moisture for improved and stable production; and (3) the amount and timing of SI are scheduled not to provide moisture stress–free conditions throughout the growing season, but to ensure a minimum amount of water available during the critical stages of crop growth that would permit optimal instead of maximum yield (Oweis, 1997).

1. Deficit Supplemental Irrigation

Deficit irrigation is a strategy for optimizing production. Crops are deliberately allowed to sustain some degree of water deficit and yield reduction (English and Raja, 1996). The adoption of deficit irrigation implies appropriate knowledge of crop water use and responses to water deficits, including the identification of critical crop growth periods, and of the economic impacts of yield reduction strategies. In a Mediterranean climate, rainwater productivity increased from 0.84 to 1.53 kg grain/m^3 of irrigation water when only one-third of the full crop water requirement was applied (Figure 2). It further increased to 2.14 kg/m^3 when two-thirds of the requirement was applied, compared to 1.06 kg/m^3 at full irrigation. The results show greater water productivity at deficit than at full irrigation. Water productivity is a suitable indicator of the performance of irrigation management under deficit irrigation of cereals (Zhang and Oweis, 1999), in analyzing the water saving in irrigation systems and management practices, and in comparing different irrigation systems.

There are several ways to manage deficit irrigation. The irrigator can reduce the irrigation depth, refilling only part of the root zone soil water capacity, or reduce the irrigation frequency by increasing the interval between successive irri-

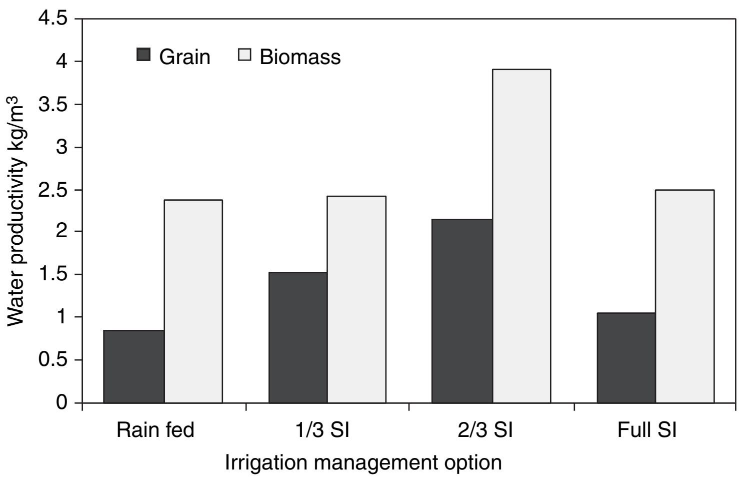

Figure 2 Water productivity of wheat under rain fed, deficit, and full SI conditions. (Adapted from Oweis, 1997.)

gations. In surface irrigation, wetting furrows alternately or placing them farther apart is one way to implement deficit irrigation. However, not all crops respond positively to deficit irrigation. This should be examined for local conditions and under different levels of water application and quality.

2. Maximizing Net Profits

An increase in crop production per unit of land or per unit of water does not necessarily increase farm profit because of the nonlinearity of crop yield with production inputs. Determining rain-fed and SI production functions is the basis for optimal economic analysis. SI production functions for wheat (Figure 4) may be developed for each rainfall zone by subtracting rainwater production function from total water production function. Because the rainfall amount cannot be controlled, the objective is to determine the optimal amount of SI that results in maximum net benefit to the farmers. Knowing the cost of irrigation water and the expected price per unit of the product, we can see that maximum profit occurs when the marginal product for water equals the price ratio of the water to the product. Figure 5 shows the amount of SI to be applied under different rainfall zones and various price ratios to maximize net profit of wheat production under SI in a Mediterranean climate.

3. Cropping Patterns and Cultural Practices

Among the management factors for more productive farming systems are the use of suitable crop varieties, improved crop rotation, sowing dates, crop density, soil fertility management, weed control, pest and disease control, and water conservation measures. SI requires crop varieties adapted to or suitable for varying amounts of water application. An appropriate variety manifests a strong response to limited water application and maintains some degree of drought tolerance. In addition, the varieties should respond to higher fertilization rates than are generally required under SI.

Given the inherent low fertility of many dry-area soils, judicious use of fertilizer is particularly important. In northern Syria, 50 kg N per hectare is sufficient under rainfed conditions. However, with water applied by SI, the crop responds to nitrogen up to 100 kg/ha, after which no further benefit is obtained. This rate of nitrogen uptake greatly improves water productivity. There must also be adequate available phosphorus in the soil so that response to nitrogen and applied irrigation is not constrained.

To obtain the optimum output of crop production per unit input of water, the mono-crop water productivity should be extended to a multi-crop water productivity. Water productivity of a multi-crop system is usually expressed in economic terms such as farm profit or revenue per unit of water used. Although economic considerations are important, they are not adequate as indicators of sustainability, environmental degradation, and natural resource conservation.

B. Water vs. Land Productivity

Land productivity (yield) and water productivity (WP) are indicators for assessing the performance of supplemental irrigation. Higher water productivity is linked with higher yields. This parallel increase in yields and water productivity, however, does not continue linearly. At some high level of yield, greater amounts of irrigation water are required to achieve additional incremental yield increase. Water productivity of wheat (Figure 3) starts to decline as yield per unit of land increases above certain levels.

It is clear that the amount of water required to achieve yield increases above 5 t/ha is much higher than that needed at lower yield levels. It would be more efficient to produce only 5 t/ha with lower water application than to achieve maximum yield with application of excessive amounts of water. The saved water would be used more efficiently if applied to new lands. This, of course, applies only when water, not land, is the limiting resource and without sufficient water to irrigate all the available land.

The association of high water productivity values with high yields has important implications for crop management in achieving efficient use of water resources in water-scarce areas (Oweis et al., 1998). Attaining higher yields with increased water productivity is economical only when the increased gains in crop yield are not offset by increased costs

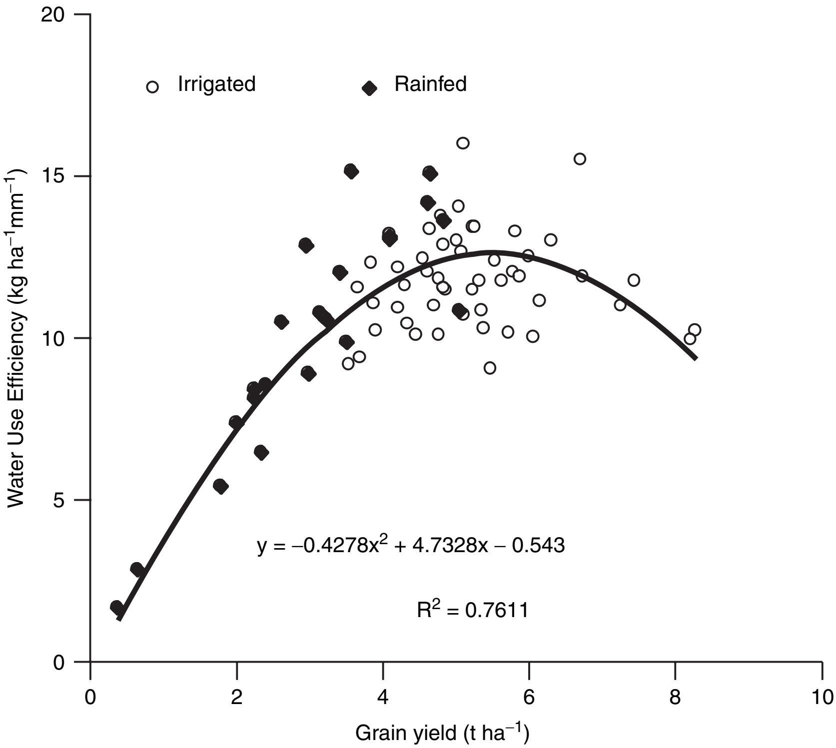

Figure 3 Relationship between crop water productivity and crop grain yield for durum wheat under SI in Syria. (From Zhang and Oweis, 1999.)

of other inputs. The curvilinear WP–yield relationship reflects the importance of attaining relatively high yields for efficient use of water. Policies for maximizing yield should be considered carefully before they are applied under water-scarce conditions. Guidelines for recommending irrigation schedules under normal water availability may need to be revised when applied in water-scarce areas.

III. WATER HARVESTING

A. The Concept and Components of the System

The drier environments, "the steppe," or, as they are called in the Arab world, *Al Badia*, occupy the vast majority of the dry

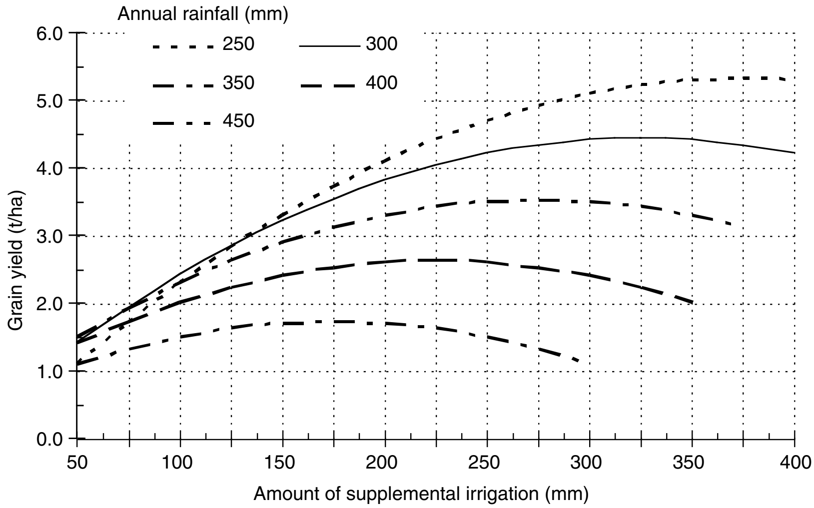

Figure 4 SI production functions for wheat in different rainfall zones in Syria. (Adapted from Oweis, 1997.)

areas. The disadvantaged people, who depend mainly on livestock grazing, generally live there. The natural resources of these areas are fragile and subject to degradation. Because of harsh natural conditions and the occurrence of drought, people increasingly migrate from these areas to the urban areas, with the associated high social and environmental costs.

Precipitation in the drier environments is generally low relative to crop requirements. It is unfavorably distributed over the crop-growing season and often comes with high intensity. It usually falls in sporadic, unpredictable storms and is mostly lost to evaporation and runoff, leaving frequent dry periods. Part of the rain returns to the atmosphere directly from the soil surface by evaporation after it falls, and part flows as surface runoff, usually joining streams and flowing to "salt sinks," where it loses quality and evaporates. A small portion of the rain joins groundwater. The overall result is that most of the rainwater in the drier environments is lost, with no benefits or productivity. As a result, rainfall in this environment cannot support economical dry farming like that in rain-fed areas (Oweis et al., 2001).

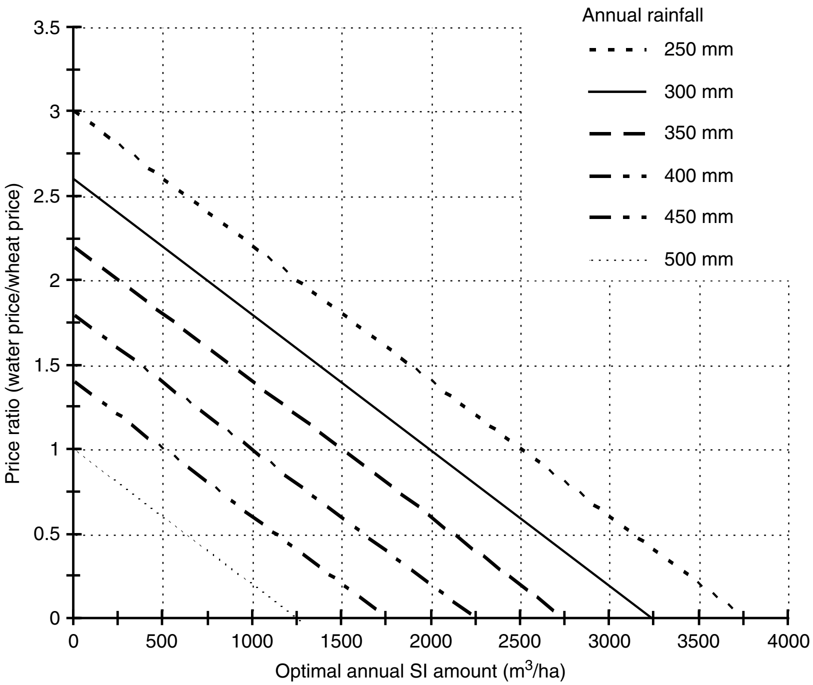

Figure 5 Optimal economical annual SI amount (m³/ha) in different rainfall zones in Syria. (Adapted from Oweis, 1997.)

Water harvesting can improve the situation and substantially increase the portion of beneficial rainfall. In agriculture, water harvesting is based on depriving part of the land of its share of rainwater to add to the share of another part. This brings the amount of water available to the target area closer to the crop water requirements so that economical agricultural production can be achieved. Water harvesting may be defined as "the process of concentrating precipitation through runoff and storing it for beneficial use."

Water harvesting is an ancient practice supported by a wealth of indigenous knowledge. Indigenous systems such as *jessour* and *meskat* in Tunisia; *tabia* in Libya; *cisterns* in north Egypt; *hafaer* in Jordan, Syria, and Sudan; and many other techniques are still in use (Oweis et al., 2004). Water harvesting may be developed to provide water for human and animal consumption, domestic and environmental purposes, and plant production. Water harvesting systems have three components:

1. *The catchment area* is the part of the land that contributes some or all of its share of rainwater to another area outside its boundaries. The catchment area can be as small as a few square meters or as large as several square kilometers. It can be agricultural, rocky, or marginal land, or even a rooftop or a paved road.
2. *The storage facility* is a place where runoff water is held from the time it is collected until it is used. Storage can be in surface reservoirs, in subsurface reservoirs such as cisterns, in the soil profile as soil moisture, or in groundwater aquifers.
3. *The target area* is where the harvested water is used. In agricultural production, the target is the plant or animal, whereas in domestic use, it is the human being or the enterprise and its needs.

B. Water Harvesting Techniques

Water harvesting techniques may be classified into two major types, based on the size of the catchment (Figure 6): micro-catchment systems and macro-catchment systems (Oweis et al., 2001).

1. Micro-Catchment Systems

Surface runoff in micro-catchment systems is collected from small catchments (usually less than 1000 m^2) and applied to an adjacent agricultural area, where it is stored in the root zone and used directly by plants. The target area may be planted with trees, bushes, or annual crops. The farmer has control, within the farm, over both the catchments and the target areas. All the components of the system are constructed inside the farm boundaries, which provides a maintenance and management advantage. But because of the loss of pro-

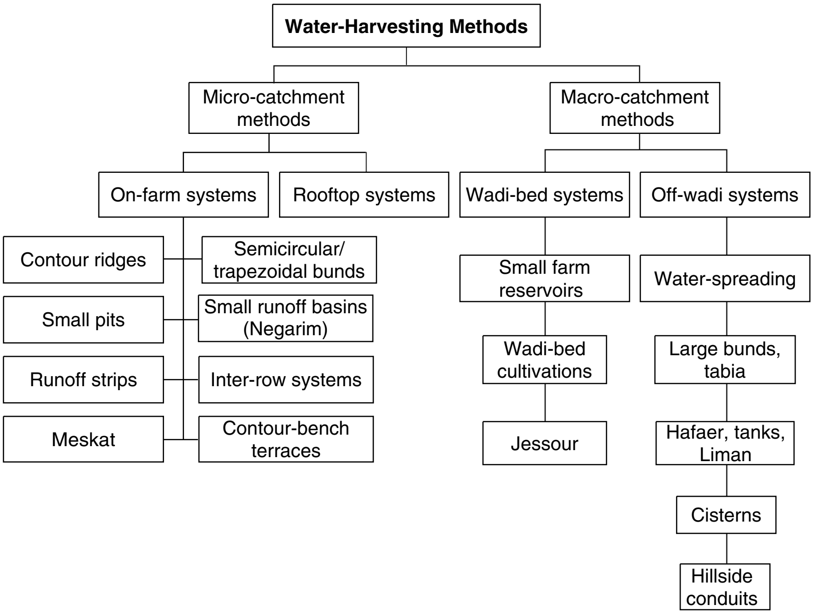

Figure 6 Classification of major rainwater harvesting systems in the dry areas. (From Oweis et al., 2001.)

ductive land it is practiced only in the drier environments, where cropping is so risky that farmers are willing to allocate part of their farm to be used as a catchment. They are simple in design and may be constructed at low cost. Therefore, they are easy to replicate and adapt. They have higher runoff efficiency than the macro-catchment systems and usually do not need a water conveyance system. Soil erosion may be controlled and sediment directed to settle in the cultivated area. These systems generally require continuous maintenance, with relatively high labor input. The most important micro-catchment water harvesting systems in the dry areas are described below.

a. Contour Ridges

Contour ridges consist of bunds, or ridges, constructed along the contour line at an interval of, usually, between 5 and 20 m. A 1- to 2-m strip upstream of the ridge is for cultivation, and the rest constitutes the catchment. The height of the ridges varies according to the slope and the expected depth of the runoff water retained behind it. The bunds may be reinforced by stones when necessary. This is a simple technique, which can be implemented by the farmers themselves. Bunds can be formed manually, with animal-driven equipment, or by tractors fitted with suitable implements. Ridges may be constructed on a wide range of slopes, from 1 to 50%.

Contour ridges are important for supporting the regeneration and new plantations of forage, grasses, and hardy trees on mild to steep slopes in the steppe (*badia*). In the semiarid tropics, they are used for the arable cropping of sorghum, millet, cowpeas, and beans. This system is sometimes combined with other techniques (such as the *zay* system) or with *in situ* water conservation techniques (such as the tied-ridge system) in the semiarid tropics.

b. Semicircular and Trapezoidal Bunds

Semicircular and trapezoidal bunds are earthen bunds created with spacing sufficient to provide the required runoff water for the plants. Usually, they are built in staggered rows. The technique can be used on an even, flat slope, but also on slopes up to 15%. The technique is used mainly for rangeland rehabilitation or fodder production, but can also be used for growing trees, shrubs, and, in some cases, field crops and vegetables.

c. Small Pits

The most famous pitting system is the *zay* system used in Burkina Faso. This form of pitting consists of digging holes 5–15 cm deep. Manure and grasses are mixed with some of the soil and put into the *zay*. The rest of the soil is used to form a small dike, down slope of the pit. Pits are used in combination with bunds to conserve runoff, which is slowed by the bunds. Pits are excellent for rehabilitating degraded agricultural lands. However, labor requirements for digging the *zay* are high and may constitute a large financial investment, year after year. This is because the pits have to be restored after each tillage operation. A special disk plow may be adjusted to create small pits for range rehabilitation.

d. Small Runoff Basins

Sometimes called *Negarim*, these runoff basins are small and of a rectangular or elongated diamond shape; they are surrounded by low earth bunds. *Negarim* work best on smooth ground, and their optimal dimensions are 5–10 m wide by 10–25 m long. They can be constructed on almost any slope, including very gentle ones (1–2% slopes), but on slopes above 5%, soil erosion may occur, and the bund height should be increased. They are most suitable for growing tree crops like pistachios, apricots, olives, almonds, and pomegranates, but they may be used for other crops. When used to grow trees, the soil should be deep enough to hold sufficient water for the entire dry season.

e. Runoff Strips

This technique is applied on gentle slopes and is used to support field crops in drier environments (such as barley in the *badia*), where production is usually risky or has a low yield. In this technique, the farm is divided into strips following contour lines. One strip is used as a catchment and the strip downstream is cropped. The cropped strip should not be too wide (1–3 m), and the catchment width should be determined with a view to providing the required runoff water to the cropped area. The same cropped strips are cultivated every year. Clearing and compaction may be implemented to improve runoff.

f. Contour Bench Terraces

Contour bench terraces are constructed on very steep sloping lands and combine soil-and-water conservation and water harvesting techniques. Cropping terraces are usually built to be level. Supported by stone walls, they slow water and control erosion. Steeper, noncropped areas between the terraces supply additional runoff water. The terraces contain drains to safely release excess water. They are used to grow trees and bushes but are rarely used for field crops. Some examples of this technique can be seen in the historic bench terraces in Yemen. Because they are constructed in steep mountain areas, most of the work is done by hand.

g. Rooftop Systems

Rooftop and courtyard systems collect and store rainwater from the surfaces of houses, large buildings, greenhouses, courtyards, and similar impermeable surfaces. Farmers usually avoid storing the runoff provided by the first rains to ensure cleaner water for drinking. If water is collected from soil surfaces, the runoff has to pass through a settling basin before it is stored.

The water collected is used mainly for drinking and other domestic purposes, especially in rural areas where there is no tap water. Extra water may be used to support domestic gardens. It provides a low-cost water supply for humans and animals in remote areas.

2. Macro-Catchment Systems

Macro-catchment systems collect runoff water from relatively large catchments, such as natural rangeland or a mountainous area, mostly outside farm boundaries, where individual farmers have little or no control. Water flows in temporary (ephemeral) streams called *wadi* and is stored in surface or subsurface reservoirs, but it can also be stored in the soil profile for direct use by crops. Sometimes water is stored in aquifers as a recharge system. Generally, runoff capture, per unit area of catchment, is much lower than for micro-catchments, ranging from a few percent to 50% of annual rainfall.

One of the most important problems associated with these systems involves water rights and the distribution of water, both between the catchment and cultivated areas and between various users in the upstream and downstream areas of the watershed. An integrated watershed development approach may overcome this problem. The most common macro-catchment systems are discussed below.

a. Small Farm Reservoirs

Farmers who have a *wadi* passing through their lands can build a small dam to store runoff water. The water can subsequently be used to irrigate crops or for domestic and animal consumption. These reservoirs are usually small, but may range in capacity from 1,000 to 500,000 m^3. The most important aspect of this system is the provision of a spillway with sufficient capacity to allow for the excessive peak flows. Most of the small farm reservoirs built by farmers in the rangelands (*badia*) have been washed away because they lacked spillway facilities or because their spillway capacity was insufficient. Small farm reservoirs are very effective in the *badia* environment. They can supply water to all crops, thus improving and stabilizing production. Moreover, the benefits to the environment are substantial.

b. Wadi-Bed Cultivation

Cultivation is very common in *wadi* beds with slight slopes. Because of slow water velocity, eroded sediment usually settles in the *wadi* bed and creates good agricultural lands. This may occur naturally or result from the construction of a small dam or dyke across the *wadi*. This technique is commonly used with fruit trees and other high-value crops. It can also be helpful for improving rangelands on marginal soils. The main problems associated with this type of water harvesting system are the costs and the maintenance of the walls.

c. Jessour

Jessour is an Arabic term given to a widespread indigenous system in southern Tunisia. Cross-wadi walls are made of either earth or stones, or both, and always have a spillway—usually made of stone. Over a period of years, while water is stopped behind these walls, sediment settles and accumulates, creating new land that is planted with figs and olives, but which may also be used for other crops. Usually, a series of *Jessour* are placed along the *wadi*, which originates from a mountainous catchment. These systems require maintenance to keep them in good repair. Because the importance of these systems for food production has declined recently, maintenance has also been reduced and many systems are losing their ability to function.

d. Water-Spreading Systems

The water-spreading technique is also called floodwater diversion. It entails forcing part of the *wadi* flow to leave its natural course and go to nearby areas, where it is applied to support crops. This water is stored solely in the root zone of the crops to supplement rainfall. The water is usually diverted by building a structure across a stream to raise the water level above the areas to be irrigated. Water can then be directed by a levee to spread to farms at one or both sides of the *wadi*.

e. *Large Bunds*

Also called *tabia*, the large bund system consists of large, semicircular, trapezoidal or open V-shaped earthen bunds with a length of 10 to 100 meters and a height of one to two meters. These structures are often aligned in long staggered rows facing up the slope. The distance between adjacent bunds on the contour is usually half the length of each bund. Large bunds are usually constructed using machinery. They support trees, shrubs, and annual crops but also support sorghum and millet in sub-Saharan Africa.

f. *Tanks and Hafaer*

Tanks and *hafaer* usually consist of earthen reservoirs, dug into the ground in gently sloping areas that receive runoff water either as a result of diversion from *wadi* or from a large catchment area. The so-called “Roman ponds” are indigenous tanks usually built with stonewalls. The capacity of these ponds ranges from a few thousand cubic meters in the case of the *hafaer* to tens of thousands of cubic meters in the case of tanks. Tanks are very common in India, where they support more than 3 million hectare of cultivated lands. *Hafaer* are mostly used to store water for human and animal consumption. They are common in West Asia and North Africa.

g. *Cisterns*

Cisterns are indigenous subsurface reservoirs with a capacity ranging from 10 to 500 m^3. They are basically used for human and animal water consumption. In many areas they are dug into the rock and have a small capacity. In northwest Egypt, farmers dig large cisterns (200–300 m^3) in earth deposits, underneath a layer of solid rock. The rock layer forms the ceiling of the cistern, whereas the walls are covered by impermeable plaster materials. Modern concrete cisterns are being constructed in areas where a rocky layer does not exist. In this system, runoff water is collected from an adjacent catchment or is channeled in from a more remote one. The first rainwater runoff of the season is usually diverted from the cistern to reduce pollution. Settling basins are sometimes constructed to reduce the amount of sediment. A bucket and rope are used to draw water from the cistern.

Cisterns remain the only source of drinking water for humans and animals in many dry areas, and the role they play in maintaining rural populations in these areas is vital. In addition to their more usual domestic purposes, cisterns are now also used to support domestic gardens. The problems associated with this system include the cost of construction, the cistern's limited capacity, and influx of sediment and pollutants from the catchment.

h. Hillside-Runoff Systems

In Pakistan, this technique is also called *sylaba* or *sailaba*. Runoff water flowing downhill is directed, before joining *wadi* by small conduits, to flat fields at the foot of the hill. Fields are leveled and surrounded by levees. A spillway is used to drain excess water from one field to another farther downstream. When all the fields in a series are filled, water is allowed to flow into the *wadi*. When several feeder canals are to be constructed, distribution basins are useful. This is an ideal system with which to utilize runoff from bare or sparsely vegetated hilly or mountainous areas.

C. Water Harvesting for Supplemental Irrigation

Where groundwater or surface water is not available for supplemental irrigation, water harvesting can be used to provide the required amounts during the rain season. The system includes surface or subsurface storage facilities ranging from an on-farm pond or tank to a small dam constructed across the flow of a *wadi* with an ephemeral stream. It is highly recommended when inter-seasonal rainfall distribution and/or variability are so high that crop water requirements cannot be reasonably met. In this case, the collected runoff is stored for later use as supplemental irrigation (Oweis et al., 1999). Important factors include storage capacity, location, and safety of storage structures. Two major problems associated with storing water for agriculture are evaporation and seepage losses. Following are management options proven to be feasible in this regard (Oweis and Taimeh, 2001):

1. Harvested water should be transferred from the reservoir to be stored in the soil as soon as possible after collection. Storing water in the soil profile for direct use by crops in the cooler season saves substantial evaporation losses that normally occur during the high evaporative demand period. Extending the use of the collected water to the hot season reduces its productivity because of higher evaporation and seepage losses.
2. Emptying the reservoir early in the winter provides more capacity for following runoff events. Large areas can be cultivated with reasonable risk.
3. Spillways with sufficient capacity are vital for small earth dams constructed across the stream.

IV. CONCLUSIONS

In the dry areas, where water is most scarce, land is fragile and drought can inflict severe hardship on already poor populations. Using water most efficiently can help alleviate the problems of water scarcity and drought. Among the numerous techniques for improving water use efficiency, the most effective are supplemental irrigation and water harvesting.

Supplemental irrigation has great potential for increasing water productivity in rain fed areas. Furthermore, it can be a basis for water management strategies to alleviate the effects of drought. Reallocating water resources to rainfed crops during drought can save crops and reduce negative economic consequences in rural areas. However, to maximize the benefits of SI, other inputs and cultural practices must also be optimized. Limitations to implementing supplemental irrigation include availability of irrigation water, cost of conveyance and application, and lack of simple means of water scheduling. In many places, high profits have encouraged farmers to deplete groundwater aquifers. Appropriate policies and institutions are needed for optimal use of this practice.

Water harvesting is one of the few options available for economic agricultural development and environmental protection in the drier environments. Furthermore, it effectively combats desertification and enhances the resilience of the communities and ecosystem under drought. Success stories are numerous and technical solutions are available for most situations. The fact that farmers have not widely adopted water harvesting has been attributed to socioeconomic and policy factors, but the main reason has been lack of community participation in developing and implementing improved technologies. Property and water rights are not favorable to development of water harvesting in most of the dry areas. New policies and institutions are required to overcome this problem. It is vital that concerned communities be involved in development from the planning to the implementation phases. Applying the integrated natural resource management approach helps integrate various aspects and avoid the conflicts of water harvesting and supplemental irrigation.

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