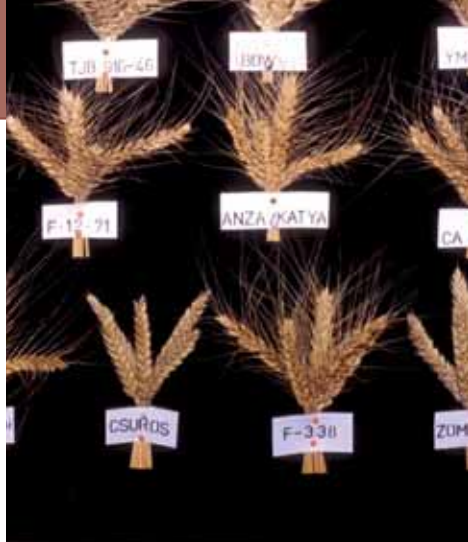


# *Enhancing cereal production in Drylands*

Grain production in dryland areas must be improved to help meet the requirements of a growing world population, urbanisation and the transition to meat-rich diets. A major contribution to this improvement will be the capture and use of a greater portion of the limited and highly variable precipitation in dryland areas. Several approaches and practices of water and soil conservation and management can increase water-use efficiency, thus increasing yields and reducing the likelihood of crop failure.

One of the difficulties with crop production in dryland regions is the extreme variation in precipitation and, therefore, yields between years. Annual precipitation in dryland regions commonly ranges from less than half of average in a dry year to more than twice average in a wet year, which renders the use of averages of little use in planning agricultural and natural resource development. Ephemeral streams are the norm rather than perennial streams and it is not uncommon for perennial streams originating from higher elevations (orographic rainfall) to become intermittent downstream. As a consequence of the highly variable annual precipitation, yields can



vary from zero to about three times average. Much of the precipitation in dryland regions occurs during high-intensity localized convective storms which result in a high level of spatial variation in rainfall – flash floods can transform a dry channel into a torrent in hours resulting in significant runoff while a channel a few km away may be completely dry (Brooks and Tayaa, 2002). The development and implementation of technologies that reduce the losses following rainfall events, including flash floods, could increase crop yields considerably.

Cereal yields in drylands could be increased and the year-to-year yield variability could be reduced if substantial effort and capital were invested. Investment in dryland agriculture represents a more environmentally sustainable and lower-cost alternative to the large amounts of capital being used to develop additional irrigated lands. Examples of the cost of developing additional irrigated lands are: US\$8 300/ha for sub-Saharan Africa, US\$6 700/ha for North Africa and the Near East (FAO, 1995), and US\$12 300/ha for Baluchistan Province in Pakistan (Venkataraman, 1999). More recent irrigation development costs are available at AQUASTAT, 2008. In comparison, the costs of dryland improvement by water harvesting are in the order of US\$300 to 5 000/ha (Oweis, Prinz and Hachum, 2001). While this improved cropland still would not be as reliable as irrigated land for cereal production because of droughts, such an investment could improve long-term average yields and yield stability significantly.

An important option for grain and other agricultural production in drylands is water harvesting. Water harvesting, which includes runoff farming, runoff storage and dry farming using fallow storage, can be less costly than irrigation and can be developed locally depending on rainfall and land conditions (Ben-Asher, 1988; Reij *et al.*, 1988); FAO, 1991; Suleman *et al.*, 1995).

A major difference between irrigation and water harvesting is the farmer's control over timing. Water can only be harvested when there is precipitation, so there is no assurance against crop failure in years when the precipitation is so low that there is little or no runoff or storage. This lack of security in water-harvesting schemes

compared with irrigated land is one reason why lending institutions and development organizations have been reluctant or unwilling to invest in water-harvesting schemes. However, the time may be right to rethink investment in water-harvesting practices. There is sufficient rainfall and soils information in most dryland regions, coupled with models that can analyse and determine probabilities, to design water-harvesting schemes that will improve crop production in the majority of years. These schemes may be more cost-effective than developing additional irrigated lands where water resources are limited. More importantly, these schemes can be developed in areas where there is no water available for irrigation.

## WATER-USE EFFICIENCY

Water-use efficiency is an important concept for understanding soil-crop systems and designing practices for water conservation (Cooper *et al.*, 1987; Howell, 1990; Musick *et al.*, 1994; Rockström, 2000; Australian Centre for International Agricultural Research, 2002). It is defined as the amount of harvestable product produced per unit of evapotranspiration between the dates when the crop is seeded and harvested, commonly expressed in kilograms per cubic metre. Evapotranspiration is the sum of the amounts of water transpired by the crop and lost by evaporation from the soil surface.

Biomass production, grain yield, transpiration and evapotranspiration are related and are contributing factors to water-use efficiency. In years of below-average precipitation, the threshold amount of evapotranspiration may not be met or only exceeded by a small amount; therefore, little or no grain is produced. Just a small amount of additional water can increase yields dramatically once the threshold amount has been reached. For example, sorghum grown in semi-arid regions requires about 100 mm of seasonal evapotranspiration before any grain is produced (Stewart and Steiner, 1990). About 15 kg/ha of sorghum grain can be produced for every additional millimetre of evapotranspiration.

Data from Bushland, Texas, in the semi-arid Great Plains of the United States of America, for grain sorghum (Stewart and Steiner, 1990), maize

(Howell, 1998), and wheat (Musick *et al.*, 1994) are summarized and compared in Figure 5. Grain sorghum has a yield advantage over maize where seasonal evapotranspiration is limited because it requires less water to initiate grain production. However, once the threshold value for initiating grain production has been met, maize produces more grain for each additional unit of water than either grain sorghum or wheat. The relationships shown in Figure 5 indicate why maize is usually the crop of choice under favourable water conditions and why grain sorghum performs best when water resources are limited. An understanding of these relationships coupled with information about the probabilities of seasonal precipitation and the amount of stored plant-available water in the rootzone at seeding time allows producers to assess production risk.

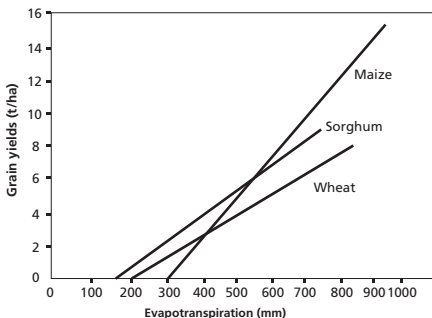
Stewart, Jones and Unger (1993) compared annual cropping of wheat at three semi-arid locations in Australia, China and the United States of America (Annex 3, Table 3). The percentage of total precipitation used for evapotranspiration was similar for all three locations at about 65 percent. In all locations, plant-available water decreased during the growing season and increased during the fallow period. However, the change was considerably less for the location in Texas in the United States of America. This had less precipitation during the fallow period, and a very high potential evapotranspiration; it is

the most arid of the three locations. While total precipitation was greater at the Texas site than at the China site, actual evapotranspiration during the wheat-growing season was also greater. The site in China had a much higher yield, and a water-use efficiency of  $0.47 \text{ kg/m}^3$  compared with  $0.31 \text{ kg/m}^3$  for the Texas location. Water-use efficiency values for wheat grown in humid regions or under irrigation often exceed  $1.25 \text{ kg/m}^3$  and values as high as  $1.9 \text{ kg/m}^3$  are reported in the literature (Musick and Porter, 1990).

Figure 6 shows the relationships between grain yield of wheat and seasonal water use for the sites in Texas (United States of America) and China. At both locations, about 200 mm of evapotranspiration were required before any grain was produced. However, for each additional millimetre of water use, about 12 kg/ha of grain was produced at the Texas site compared with about 25 kg/ha at the China site. The relationships shown in Figure 7 illustrate the impact of technologies that increase the amount of water available for crop use and the resulting grain yield, but the degree of impact will be site-specific.

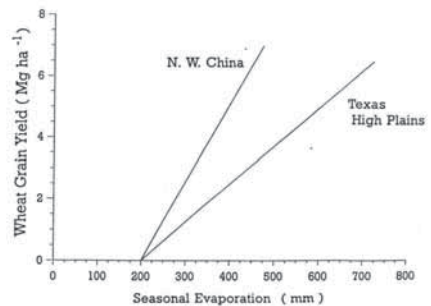
Increased soil-water storage also influences the effects of fertilizer and other inputs. FAO (2000b) developed a generalized relationship between water use and cereal grain yields showing that the impact of inputs increased sharply with

FIGURE 5  
Evapotranspiration and grain yield for maize, sorghum and wheat



Sources: Howell, 1998 (maize); Stewart and Steiner, 1990 (sorghum); Musick *et al.*, 1994 (wheat).

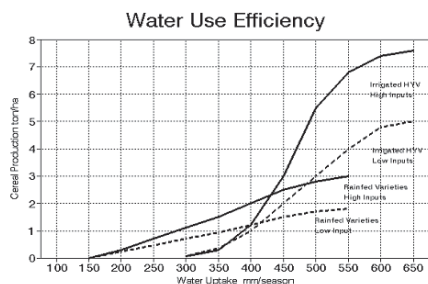
FIGURE 6  
Wheat yield and seasonal evapotranspiration for two semi-arid regions



Source: Stewart, Jones and Unger, 1993.

FIGURE 7

### Effects of increase evapotranspiration on the water-use efficiency of cereal production



Source: FAO, 2000b.

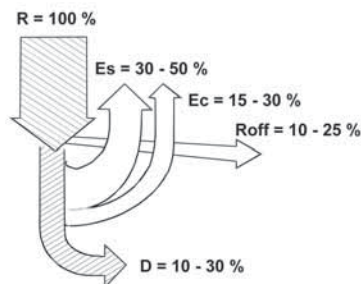
increased water availability (Figure 7). There are crop models that estimate grain yields for various cereals based on average and predicted amounts of evapotranspiration (FAO, 2003c). While not necessarily accurate for a specific year, these models are extremely useful in assessing the suitability of an area over a number of years.

The fact that cereal yields tend to increase in proportion to increases in evapotranspiration makes it imperative that dryland farming systems focus on reducing runoff and evaporation from the soil surface (Lal and Pierce, 1991). This allows a higher proportion of the limited precipitation to be used for transpiration, leading directly to higher yields. This is even more important where fertilizer and other inputs are used to allow a higher nutrient-limited yield.

The major emphasis in dryland farming is to capture, store and utilize highly variable and scarce precipitation. An overview of the partitioning of rainfall in the semi-arid tropics is shown in Figure 8. A large proportion of non-productive water flow in the dryland crop-water balance indicates problems that may be related to soil-fertility depletion or soil physical deterioration (especially reduced infiltration and waterholding capacity) through oxidation of organic matter. As much as 70 percent of precipitation may not be used directly for crop production. The focus must be to use more of the water as transpiration and lose less to runoff

FIGURE 8

### General overview of rainfall partitioning in semi-arid regions



Note: R = rainfall; Es = soil evaporation and interception; Ec = plant transpiration; D = drainage; Roff = surface runoff.

and evaporation from the soil surface (Cooper *et al.*, 1987; Stewart and Steiner, 1990; Howell, 1990; Musick *et al.*, 1994; Rockström, 2000; Australian Centre for International Agricultural Research, 2002). This can be done by two different management strategies: *in situ* water conservation; and water harvesting.

*In situ* water conservation aims to prevent runoff and keep as much rainfall as possible where it falls, and then minimize evaporation, so that the water remains available for the crop. Water harvesting (runoff agriculture and runoff storage) is the collection and concentration of rainwater and runoff and its productive use for crops, livestock or domestic use (Smith and Critchley, 1983; Reij *et al.*, 1988; Oweis *et al.*, 2001). Water-harvesting practices are often designed to enhance runoff in one area so that the water can be used by a crop on an adjacent area or stored and used later, often at another site.

## IN SITU WATER CONSERVATION

The concept of “blue” and “green” water is used to distinguish between two fundamentally different elements of the water cycle (Falkenmark, 1995). After atmospheric precipitation reaches the land surface, it divides into different sections which pursue the terrestrial part of the hydrological cycle along different paths. UNDP (2006) estimates that of the 110 000 km<sup>3</sup> of precipitation falling annually on the land surface, about 40 000

km<sup>3</sup> is converted into surface runoff and aquifer recharge (blue water) and about 70 000 km<sup>3</sup> is stored in the soil and returned to the atmosphere through evaporation and transpiration by plants (green water). Rainfed agriculture uses only green water, while irrigated agriculture uses blue water in addition to green water. UNDP (2006) estimated that crop production uses up to 13 percent (9 000 km<sup>3</sup>/yr) of the green water while the remaining 87 percent is used by the non-domesticated vegetation including forests and rangelands. It is further estimated that about 2 300 km<sup>3</sup>/yr is withdrawn from rivers and aquifers for irrigation, but only about 900 km<sup>3</sup> is effectively consumed by crops. Molden *et al.* (2007) states that 80 percent of agricultural evapotranspiration is directly from green water, with the rest from blue water sources.

Controlling runoff is a primary objective of any dryland cropping system. Although total precipitation in dryland regions is limiting, high-intensity storms are common and the amounts of runoff (“blue” water – Falkenmark, 1995) can be significant. The amount of runoff is often largely independent of slope. Rockwood and Lal (1974) reported about 20 percent runoff from bare fallow land in Nigeria regardless of whether the slope was 1, 5, 10 or 15 percent. While the runoff amounts were similar, the amount of erosion was strongly dependent on the slope.

The potential for runoff increases with a decline in SOM because soil structure deteriorates and surface crusts form. Runoff can be particularly high on clayey or silty soils. Runoff should be controlled by prevention or collection where possible. However, runoff prevention by itself does not ensure infiltration and storage for use by crops (“green” water – Falkenmark, 1995) because some of the water temporarily stored on the surface may evaporate before it can infiltrate (“white” water – Falkenmark, 1995). In other cases, infiltrated water may move below the root-zone.

Several technologies and strategies have been developed that clearly demonstrate that the limited precipitation in dryland areas can be used more efficiently. However, they have not been widely accepted for various reasons. Unlike irrigation that generally results in large,

consistent, and predictable yield increases every year, dryland technologies may not result in any increase for one or even several succeeding years so farmers often become reluctant to continue the practice. An even more serious constraint for many dryland regions is the competing uses for crop residues. Many of the most successful *in situ* water conservation practices depend on leaving crop residues on the soil surface as a mulch to conserve water and enhance soil organic matter conditions. In many dryland areas, crop residues are critically needed for fuel or livestock feed and farmers perceive that these short-term benefits are greater than the long-term benefits that might result from sustaining the soil quality.

Kerr (2002) reviewed many watershed programs in India where water conservation technologies have been promoted vigorously. He stated that although the historic focus of most Indian soil and water conservation projects had been on mechanical measures such as trapping runoff water behind mechanical or vegetative barriers, it was widely recognized that conservation begins with sound agronomic practices such as maintaining soil cover and cultivating across the slope to encourage infiltration and reduce evaporation. However, Kerr (2002) surveyed farmers about a variety of conservation-oriented agronomic practices, including strict contour cultivation, cultivation across the slope, retaining stubble in the plot, and applying mulches to cover bare soil. Of all these practices, Kerr found that the only one practiced by more than a handful of farmers was cultivation across the slope. Farmers indicated that they recognized the value of applying mulches and retaining stubble in the fields throughout the dry season, but they rarely carried out these practices because of the high opportunity cost of forgoing use of the cut stubble for fuel and feed.

Even though *in situ* water conservation practices have not been widely accepted in many dryland regions because of various constraints, it is critically important that technologies and strategies for these areas continue to be developed and made known to farmers and policy makers so that they will become used when conditions warrant their adoption. In irrigated areas, transferring technology was relatively simple because improved seeds, fertilizers, and other inputs were quickly adopted because yields and

profits were increased with little risk. In dryland areas, the success of technical interventions often depends on location-specific biophysical and socioeconomic conditions and often requires collective action by local people. Technologies that are successful one year may or may not be successful the succeeding year because of widely variable climatic conditions. However, the technologies presented below have proven effective in various dryland regions sufficiently often to warrant careful consideration.

### TERRACES

Terraces (Plates 7 and 8) have been used for centuries as a way of controlling runoff and erosion. Because of the diversity in conditions where terraces are used, careful design is necessary to determine the most appropriate type of terrace for a specific location.

Bench terraces are perhaps the oldest type of terrace. They were used primarily in areas where the supply of agricultural land was limited and where population pressure forced cultivation up steep slopes. Early bench terraces were constructed by carrying soil from the uphill side of a strip to the lower side so that a level step or bench was formed. The steep slopes below the terraces were stabilized by vegetation or by neatly fitted stonework. Some early bench terraces are still being used successfully, e.g. radiocarbon dating indicates that the bench terraces in the Colca Valley in Peru were built at least 1 500 years ago (Sandor and Eash, 1995). The construction of terraces has continued in recent years, particularly in countries with limited land and high population pressure. In

China, more than 2.7 million ha of cropland were terraced from about 1950 to the end of 1984. This practice, combined with other measures of improved technology, resulted in a 2.8-fold increase in grain production (Huanghe River Conservancy Commission, 1988).

Despite their many benefits, the use of terraces has decreased in recent years for several reasons. They are costly to construct and maintain, furthermore terraced land is more difficult to farm, particularly with large equipment. The construction of terraces may also result in soil-fertility problems because topsoil is buried or moved downslope. Terraces are also subject to failure during large, intensive rainfall events, resulting in considerable damage that is costly to repair. Notable exceptions exist to the trend of not maintaining terraces, for example the level bench terrace system of the Colca Valley in Peruvian Andes (100 km<sup>2</sup>), and Zhuanland County, Gansu Province in China's loess plateau (1 555 km<sup>2</sup>) which have recently been rehabilitated (WOCAT, 2007).

In Yemen, one of the most extensively terraced areas in the world, there is a well-documented tradition of both dryland and irrigated farming over the past three millennia and much of the indigenous agricultural knowledge survives. Development efforts during the seventies and eighties in the north of Yemen focused on expansion of tubewell irrigation at the expense of the major land use on dryland terraces and traditional subsistence crops. Despite millions of dollars in aid, Yemen is far from agriculturally self-sufficient and its scarce water resource is

PLATE 7  
Terracing on an arid hillside



PLATE 8  
The construction of terraces assists in soil and water conservation in the Syrian Arab Republic (M.Marzot)



rapidly being depleted. Varisco (1991) explored the relevance of indigenous Yemeni knowledge of agriculture and the environment for the future of terrace farming in the country, arguing that farmer knowledge can contribute to sustainable production when integrated with modern methods and technologies. Within Yemen the existing community support networks and pride in national heritage would assist in a reinvestment effort for the existing resource of the terraces.

### CONSERVATION BENCH TERRACES

Conservation bench terraces (CBTs) or Zingg terraces are a type of rainfall multiplier. They use a part of the land surface as a catchment to provide additional runoff onto level terraces on which crops are grown. The method is particularly appropriate for large-scale mechanized farming such as the wheat/sorghum farmlands of the southwest of the United States of America, where the method was pioneered by Zingg in 1955. Extensive trials in six western states with lowest rainfall compared the Zingg terraces with conventional level terraces and all-over bench terracing. The conclusion was that these types were as effective at controlling erosion as the other two practices, and more effective at reducing overall runoff. The data from these trials provided general guidelines on the method, but standard designs should be avoided because of the wide variation in the conditions of the soil, rainfall and farming system. The best way of applying the system in a particular situation should always be investigated locally.

The main application of the system is to increase the yield and the reliability of yield where rainfall is nearly sufficient for crop production (300–600 mm). Because of the high cost of installation of CBTs, it is not appropriate at very low rainfalls. Improving the probability of obtaining a reasonable crop may be more important than numerical increase in yield (FAO, 1987).

### CONTOUR FURROWS

Contour furrows (or contour bunds and desert strip farming) are variations on the theme of surface manipulation that require less soil movement than conservation bench terraces, and are more likely to be used by small farmers, or in lower rainfall areas (Plate 9). The cropping is usually intermittent on strips or in rows, with the catchment area left fallow (FAO, 1987). The principle is the same as with CBTs, that is, to collect runoff from the catchment to improve soil moisture on the cropped area.

Where the contour furrows are not laid out precisely on the contour, or are built with some irregularities, there may be a danger of uneven depths of ponding behind the bank. This can be reduced by smaller bunds at right angles. However, as with tied ridging, these bunds should be lower in height than the main ridges so that any overtopping it will be laterally along the contour and not over the bund and down the slope. Sometimes, the emphasis is on the excavated furrow which collects water, so that in exceptional storms the runoff can overflow without damage.

### CONTOUR BUNDS

Contour bunds (Plate 10) have been used in Kenya. At one site, a satisfactory sorghum crop was grown on only 270 mm of rainfall with a catchment ratio of 2:1. It was estimated that runoff from the catchment was 30 percent, giving 166 mm of runoff, and 432 mm available to the plants (Smith and Critchley, 1983).

Contour bunds are also used in Ethiopia for a combination of soil conservation and water conservation. The bunds are built on a level grade with ties in the basin. A stone wall is built on the lower side of the earth bund in an attempt to reduce damage if the basin is overtopped (Hurni, 1984).

PLATE 9  
Cabbage crop planted near contour furrows  
(L. Dematteis)



PLATE 10

Farmers working on the construction of contour bunds (G. Bizzari)



PLATE 11

Laser-levelled basin irrigation in the Tadla region, Morocco (H.Bartali)



### LAND LEVELLING WITH LASER AND MINI BENCHES

Land levelling with laser (Plate 11) is one of the most effective means of conserving runoff and preventing soil erosion (Box 1). However, because it is also the most expensive, this method has not been used widely except in areas with extreme land and water shortages. As a practical alternative to land levelling, narrow minibenches can be constructed economically on gentle (up to 2 percent) slopes (Jones, Unger and Fryrear, 1985). Soil cuts are relatively shallow and this reduces significantly the soil-fertility problems that are normally associated with the redistribution of large volumes of soil. Minibenches do not require much soil to be moved, making the system much less expensive to construct.

### TIED RIDGES

Another alternative to land levelling is the use of furrow dyking, also called tied-ridging (Box 2). This is a proven soil- and water-conservation method under both mechanized and labour-intensive systems and it is used in many areas of the world. Furrow dykes retain precipitation on the soil surface until it can infiltrate. They are most effective where they are constructed on the contour. Seeding crops on the contour can be adapted to all types of tillage, including reduced-tillage and no-tillage systems, and this is highly recommended. Under mechanized systems, the furrow dykes are usually destroyed by tillage and have to be reconstructed each year. They can also become an obstacle during cultivation or harvesting operations. Perhaps the most important reason why more farmers do not adopt this technology is that, while the

BOX 1

### Land levelling with laser in Morocco

New strategies for improving the already available irrigation systems are being devised in Morocco. For example, in order to improve on-farm irrigation, laser-levelled basin irrigation has been introduced on a number of farms in the Tadla region.

Laser-levelled basin irrigation has been widely used for field crops in the United States of America and for rice cultivation worldwide. It is particularly well adapted to flat terrain and heavy soils. Demonstrations on some farms showed substantial benefits in water saving of 20 percent and crop increases of 30 percent. Other farm inputs were improved by 10 percent and there were labour savings of 50 percent. The uniformity of irrigation was about 90 percent.

In principle, basin irrigation is the simplest of all surface irrigation methods. The key is to design the size of the basins to flood the entire area in a reasonable time, so that the depth of water is applied with a high degree of uniformity over the entire basin. Therefore, optimal sizes vary with soil types and stream flows. Very large basins served by flows of up to 150 litres/second are used in the United States of America. The method is not appropriate for crops that are sensitive to wet soil conditions around the stems or for crops on soils that crust badly when flooded. A disadvantage of basin irrigation is the interference of levees with the movement of cultivation and harvesting equipment (IPTRID, 2001).



additional effort is considerable, this does not increase yields in some years. Data from the Texas High Plains, USA, showed that the average runoff during the grain sorghum season was 25 mm; theoretically enough to increase grain yields by about 375 kg/ha (Stewart and Steiner, 1990). During the period of the study, there was little or no runoff in half the years and, often, two or three years without runoff occurred in sequence. Farmers often discontinue the practice before a sufficiently favourable response is obtained that would convince them to use the practice every year.

While the emphasis in semi-arid regions is usually on preventing runoff to increase the amount of water available for crop production, the prevention of runoff can lead to serious erosion problems if too much water accumulates. Water-management strategies must be site-specific. The most important factors are the soil-storage characteristics and the distribution of rainfall with respect to the growing season. In Hyderabad, India, El-Swaify *et al.* (1985) showed that the traditional cropping system on Vertisols resulted in 28 percent of the annual precipitation being lost as runoff, and 9 percent lost as deep percolation. On Luvisols (Alfisols), they found that the extent of runoff was similar (26 percent) but that percolation was 33 percent. There were substantial losses to percolation on both soils, and this occurred for all years of the study. The reason for these losses is that precipitation during the wet season exceeds the waterholding capacity of the soil profile. Eliminating runoff in these areas can result in serious waterlogging, particularly on Vertisols and other soils with high clay content. This is in contrast to other semi-arid regions where precipitation is often insufficient to fully recharge the soil profile.

Selecting the strategy for water conservation requires careful consideration of local conditions. Dhruva and Babu (1985) propose doing it by comparing rainfall with crop requirements giving three conditions:

- Where precipitation is less than crop requirements, the strategy includes land treatment to increase runoff onto cropped areas, fallowing for water conservation, and the use of drought-tolerant crops with suitable management practices.

- Where precipitation is equal to crop requirements, the strategy is local conservation of precipitation, maximizing storage within the soil profile, and storage of excess runoff for subsequent use.
- Where precipitation is in excess of crop requirements, the strategy is to reduce rainfall erosion, to drain surplus runoff and store it for subsequent use.

However, the weakness of this approach is that the main feature of rainfall in semi-arid regions is that it is very erratic and completely unpredictable (Brooks and Tayaa, 2002). There can be wide variations of moisture shortage and surplus both within and between seasons. A drought year whose total rain is well below the long-term average may still include periods of excessive rain and flooding, while a high-rainfall season may include periods of drought.

This makes the choice of strategy difficult, because the desired objective may change from

#### BOX 2

##### Experiences with tied-ridging

Most experience with the use of tied ridging has resulted in improvements. For example, in Africa, the system has been beneficial not only for reducing runoff and soil loss, but also for increasing crop yield (El-Swaify *et al.*, 1985). However, in high rainfall years or in years when relatively long periods within the rainy season were very wet, significantly lower yields were reported from systems with tied ridges than from graded systems which avoided surface ponding of water. Under such conditions, tied ridging enhanced waterlogging, developed anaerobic conditions in the rootzone, resulted in excessive fertilizer leaching, and caused water-table rise in lower slope areas.

Macartney *et al.* (1971) reported that tied ridging in the United Republic of Tanzania gave higher maize yields in both low and high rainfall years. However, reports of success are more common in low rainfall years. For example, Njihia (1979) reported from Katumani in Kenya that tied ridging resulted in the production of a crop of maize in low-rainfall years when flat-planted crops gave no yield.

one season to another. In a dry area, it may be sensible to increase surface storage to improve crop yield in most years. However, in a wet year, this could cause waterlogging and reduce the yield. On the other hand, a drainage system may have the objective of increasing the runoff but also the undesired effect of exaggerating the effect of a drought. Therefore, it is not practical to classify methods according to average conditions, or to design strategies based on averages. Water management should reduce the problems caused by non-average events of flood and drought.

It may sometimes be possible to have dual-purpose strategies including methods that can be changed mid-season, for example, by opening up the ends of contour bunds to shed surplus water after a wet start to the season, or to block outlets for the opposite effect. However, not many methods allow this flexibility.

In addition to the variation in rainfall, there are other factors to consider: the soil, the land use, the farming system, and the social patterns (local lifestyles, social systems, and patterns of administration). Transferring what appear to be simple techniques requires not only the dissemination of information but also adaptation to local conditions.

## WATER HARVESTING

Harvesting rainwater can be traced back to the 9th and 10th Century (GRDC, 2008). People in south and southeast Asia collected rainwater from roofs and from simple dams constructed from brush. Rainwater has long been used in the Loess Plateau regions in China where more recently, between 1970 and 1974, about 40 000 well storage tanks of various forms were constructed (GRDC, 2008). A thin clay layer was generally laid on the bottom of the ponds to minimize seepage losses and trees were planted at the edges of the ponds to help minimize evaporation (UNEP, 1982).

Perrier and Salkini (1991) defined water harvesting as a water-management technique for growing crops in arid and semi-arid areas where rainfall is inadequate for rainfed production and irrigation water is lacking. Rainfall is collected from a modified or treated area to maximize runoff for use on a specific site such as a cultivated field,

or for storage in a cistern or a reservoir, or for aquifer recharge. This definition is very restrictive and water harvesting is generally considered much more broadly. Bamatraf (1991) stated that farmers in Yemen tend to use water-harvesting techniques where rainfall is not sufficient. Thus, several approaches can be considered, including: runoff agriculture, where runoff is concentrated on a smaller area, generally used for arable or perennial crops; and runoff storage, generally in small reservoirs, used to supplement rainfall – often in horticulture or for livestock or domestic use. In dry farming, precipitation is captured in the soil where it falls during a fallow period and used to supplement rainfall during the next cropping period.

Water harvesting is sometimes practised with the primary objective to raise the water table to promote or sustain irrigation development. This has been the focus particularly in India and has been highly promoted and subsidized by many government and non-government programs. Although there have been some notable successes that have been widely publicized, the overall impact seems to have been minimal. Kerr (2002) and Batchelor *et al.* (2002) reviewed and summarized the impact of many watershed projects in India. Batchelor *et al.* (2002) acknowledged that different forms of water harvesting have been used successfully in semi-arid areas of India for millennia as a means of protecting domestic water supplies and increasing or stabilising agricultural production. Accepted wisdom has been that rainfall should be as far as possible be harvested where it falls and that these technologies are totally benign. They found, however, emerging evidence that water harvesting in semi-arid areas, if used inappropriately, can lead to inequitable access to water resources and, in the extreme, to unreliable drinking water. Kerr (2002) concluded that quantitative analysis did not yield strong conclusions about the success of water harvesting to develop irrigation. Kerr (2002) stated that none of the projects seem to have done much to assist farmers without irrigation or to help landless people gain access to the additional water generated through project efforts.

Water harvesting discussions in this publication will focus on harvesting water in surface structures for storage and subsequent use for growing crops or vegetables. The earliest water-harvesting

structures are believed to have been built 9 000 years ago in the Edom Mountains in southern Jordan to supply drinking-water for people and animals (Oweis, 1996; Nasr, 1999). In southern Tunisia, ancient techniques such as meskat, micro-catchments, and jessour (terraces behind cross-dams in ephemeral watercourses) are still supporting olive and fig trees (Prinz and Wolfer, 1998). In Algeria, lacs collinaires (runoff storage ponds) have been used. In the caag system in the United Republic of Tanzania, floodwater from a stream is diverted and conveyed to a sequence of bunded basins used for cropping (Hatibu and Mahoo, 2000). The ancient hafirs (catchment reservoirs) in the Sudan (UNEP 2000) are still in use for domestic and livestock purposes as well as for the production of pasture and other crops. Siadat (1991) reported that in some parts of the Islamic Republic of Iran, such as Baluchistan in the southeast and Khorasan in the east, farmers have been using canal and dyke systems for centuries to spread water over parcels of cropland in order to increase soil-water storage. However, these techniques are practised in limited areas.

Water conservation and runoff storage were practised for centuries in India in an ecologically sound manner (Singh, 1995). The systems were decentralized, and the urban and rural communities played an active role in water management. Precipitation was the main source of water, most of it falling in a mere 100 hours in a year (Centre for Science and Environment, 2001). Once captured, this water met the demands for the rest of the year. These traditional water-harvesting systems declined when the provision of water with traditional decentralized systems was replaced with centralized systems. Centralized systems resulted in increasing and unsustainable dependence on groundwater sources and a gross neglect of the primary source of water – precipitation. An example is near Alwar in Rajasthan State. When the decision to sell off the trees was taken, the hills started to erode and could no longer hold the water during the few months of rains. The rivers stopped running and the wells went dry. When the wells went dry, the people who had depended on agriculture for many years could no longer grow food. In 1985, in an effort to reverse the process, the villagers began building johads, small dam-like structures. By 1986, the results were already visible. The rains

## BOX 3

**Water harvesting schemes in the desert and semi-desert areas of Africa**

This zone is characterized by very low, erratic rainfall (less than 500 mm/year). The major agricultural activity is nomadic stock raising (camels, goats, sheep and cattle). In this zone, the most important form of smallholder irrigation development is likely to be water harvesting. Spate irrigation could also be practised in occasional watercourses as well as shallow groundwater development. In some places, such practices are traditional. For example, in the Lower Omo Valley in Ethiopia (rainfall 300 mm/year), fodder and food-crop production depends almost entirely on seasonal floodwater from the River Omo and recession farming in the old river channels. Successful systems of runoff farming have also evolved in the adjacent Woito Valley.

Water harvesting is often the only alternative to making a living through semi-nomadic stock-raising or depending on famine relief. An example of the establishment of water harvesting by semi-nomadic tribes was in Turkana in northern Kenya in the early 1980s. There were reports of local resistance in the form of apathetic attitudes and inherent scepticism towards the idea that crops could be produced on what was traditionally regarded as grazing land. Once there was demonstrable success in increasing fodder production, the level of participation grew rapidly and a large number of fields came under regular cultivation producing grain, fodder and wood (Oweis, Hachum and Kijne, 1999).

filled the johads, and the riverbed retained water for a much longer period. Within just a few years, the region once labelled a “black zone” by the Rajasthan government (meaning too dry to grow anything), again had a stable groundwater level, the five rivers in the region were again flowing continuously, and the villagers had returned to growing crops in the area.

In recent years, efforts have been made to implement modern techniques of water harvesting (Boxes 3 and 4). Al Ghariani (1995) reported very promising prospects for

## BOX 4

**Assessing the feasibility of water-harvesting techniques in Tunisia**

In the arid regions of Tunisia, considerable investments are being made in maintaining the old water-harvesting techniques and introducing new ones to capture the scarce amount of rainwater (100–230 mm/year) for agricultural, domestic and environmental purposes.

A large variety of traditional methods (jessour, cisterns, etc.) and contemporary techniques (gabion, tabias, recharge wells, etc.) are found in the area. They have been playing various roles with regard to the mobilization and exploitation of rainfall and runoff waters (soil water, vegetation, flooding, aquifer recharge, etc.).

In most of the cases, the local population is aware of the environmental impacts of the introduction of new water-harvesting techniques. However, the real perception depends largely on the activity of the farmers (rainfed farming, irrigation, livestock, etc.) and their location (upstream, piedmont, downstream or coast) in the watershed. However, further refinements are needed to better include all possible impacts (positive and negative) that would occur as a result of the installation of these structures. The interactions between upstream and downstream areas have to be addressed thoroughly to ensure partitioning of natural resources between different end users. The use of a geographical information system (GIS) and information technology would be of great value in transforming the obtained results as tool for decision-makers. The latter will be used in order to assess under which agro-ecological and socio-economic conditions investment in water-harvesting measures could be a viable undertaking in dry areas.

Source: Ouessar, Sghaier and Fetoui, 2002.

runoff agriculture systems in the Libyan Arab Jamahirriya. Successful trials have resulted in the construction of 53 000 ha of terraces around Tarhuna, Misallata, Urban and Assabas. Another 1 500 ha have been terraced in the

Jabal Al-Akhdar zone for cultivation of apple and cherry trees. The traditional stone walls and small collection basins have been improved and expanded. The main constraint on further development is the availability of skilled farmers to occupy and manage these newly established runoff-based farms.

In general, four types of water-harvesting techniques are used: micro-catchments, macro-catchments, floodwater harvesting, and rooftop water harvesting. These types of water harvesting are discussed briefly here, but details on the construction and application of these systems can be found in the FAO manual for the design and construction of water harvesting schemes for plant production (FAO, 1991).

**MICRO-CATCHMENTS**

Micro-catchment water-harvesting systems consist of a distinct catchment area and a cultivated area that are adjacent to each other (Hatibu and Mahoo, 1999) with the catchment being generally less than 1 000 m<sup>2</sup>. The distance between the catchment area and the runoff receiving area is less than 100 m. These types of systems are simple, inexpensive and easily reproducible. Suleman *et al.* (1995) suggest that these systems offer significant increased cropping potential to smallholders without access to tractors in developing countries.

Several forms of micro-catchments (Box 5) have been used around the world: natural depressions, contour bunds, inter-row water harvesting, semi-circular and triangular bunds, meskats and negarims. The use of these will depend on the local conditions and the type of crop that receives the runoff water.

**MACRO-CATCHMENT**

Also called external catchments, macro-catchments (Plate 12) collect runoff from a large area located a significant distance from the cultivated area (Hatibu and Mahoo, 1999). The collected water is sometimes stored in a separate location before being used. Some types of external catchments include hillside-sheet or rill-runoff utilization, and hillside-conduit systems (Rosegrant *et al.*, 2002).

## FLOODWATER HARVESTING

Floodwater harvesting within a streambed involves blocking the water flow, causing water to concentrate in the streambed (Plate 13). The streambed area where the water collects is then cultivated. It is important to make sure that the streambed area is flat with runoff-producing slopes on the adjacent hillsides, and that the flood and growing seasons do not coincide (Reij, Mulder and Begemann, 1988).

Ephemeral stream diversion is another external catchment system that is often used to harvest rainwater. In this technique, the water in an ephemeral stream is diverted and applied to the cropped area using a series of weirs, channels, dams and bunds (Box 6).

## ROOFTOP WATER HARVESTING

- Rooftop water harvesting (Plate 14) is mainly used for domestic purposes and growing small

vegetable gardens (Box 7). It is one of the most important options for addressing household food security in drought-affected, moisture-stressed environments. This is because:

- rainwater can be more easily available in moisture-stressed areas;
- the water captured requires low levels of external energy for extraction and transportation;
- the system can be easily implemented with family labour and using local materials;
- the system has low initial investment costs;
- the water can be used for other purposes.

## FACTORS AFFECTING RUNOFF

Radder, Belgaumi and Itnal (1995) discussed the various factors governing the amount of runoff from a water-harvesting catchment area (Table 4) and summarized information from India on water-harvesting efficiencies of different surface treatments for inducing runoff (Table 5). The

### BOX 5

#### Some examples of water harvesting using micro-catchments

A decade of work in Jordan and the Syrian Arab Republic has demonstrated that micro-catchment techniques such as contour ridges for fodder shrub and pasture production have considerable potential for revegetation and combating degradation in rangelands. Where rainfall is less than 150 mm, micro-catchments economically support almond, pistachio and olive trees without supplemental irrigation. In the same area, water harvested and stored in small earth dams was used for the seasonal production of field crops. Rainfall-use efficiency can be very high using properly designed and managed water-harvesting systems. Overall system efficiency for small-basin micro-catchments in Jordan exceeded 86 percent. Where the system is not well designed and not managed properly, the efficiency drops to about 7 percent. These results reinforce the importance of combining technology development with the perceptions, needs and capabilities of the land users who will implement water harvesting (Oweis, 1997).

In the Province of Hamadan, the Islamic Republic of Iran, the use of runoff water (seilaub) is common. Rainwater is collected from sloping surfaces into channels running along slope-breaks and distributed to parcels located below the slope-breaks. In some places, water is stored in roughly constructed pools (estakhr) with a hole at the bottom that opens into a channel (djoob). The whole system is kept closed with a piece of wooden beam (dirak) which is pulled off to start irrigation. Similar pools are constructed at the openings of qanats with a low discharge capacity. As the water flows continuously, the pool remains full and can be used with a higher pressure where needed. Some of these techniques were used in the days of the ancient Persian Empire and are the product of local people's ability to manage scarce water resources on a sustainable basis (Farshad and Zinck, 1998).

In 1979, a small experimental area of micro-catchments for fuelwood trees was established with farmer participation in Burkina Faso. The farmers involved subsequently adopted these runoff-farming techniques and used them to improve their traditional erosion-control methods, thereby increasing their normal agricultural production. Fields long abandoned are now being reclaimed and farmers are increasing infiltration through the construction of simple contour bunds (Oweis, Hachum and Kijne, 1999).

PLATE 12

Upstream works enable subsequent action in the valleys. This newly recovered seasonal pond irrigated 80 ha in the 1993 rainy season (F. Paladini and R. Carucci)



PLATE 13

A farmer clears a canal on the Nile River (R. Faidutti)



most practical treatment was to compact the soil surface; this resulted in a runoff coefficient (the proportion of the precipitation leaving the catchment area as runoff) of 30–60 percent. The highest runoff achieved was about 90–95 percent when the soil surface was covered with asphalt or fibreglass sheets. These treatments are costly and require considerable maintenance.

## BOX 6

## Water spreading in eastern Sudan

In the Red Sea Province of Eastern Sudan, traditional water-spreading schemes are being rehabilitated and improved under the technical guidance of the Soil Conservation Administration. In this semi-desert region, wadi beds are the traditional sites for cropping of sorghum by the semi-nomadic population, using the moisture from natural flooding.

The improvements being introduced are large earth diversion embankments in the main or subsidiary channels, and then a series of spreading bunds or “terraces”. These bunds are usually sited on, or approximately on, the contour, and spread the diverted flow. The spacing between bunds in the almost flat landscape is not fixed but can range up to 200 m apart. Bunds are usually up to 150 m long and at least 75 cm high. Some machinery is employed, but manual labour supported by incentives is also used (FAO, 1991).

More recently, Oweis, Prinz and Hachum (2001) estimated runoff coefficients and costs of typical runoff-inducement techniques using information from locations in the Near East (Table 6). These coefficients provide information necessary for evaluating the potential of harvesting water for a given region, and the results can be coupled with water-use efficiency values to estimate the production from the harvested water. For example, if the runoff coefficient of an inducement technique is 50 percent, and it is estimated that 200 mm of annual precipitation is subject to water harvesting, then 1 000 m<sup>3</sup>/ha of water could be harvested. The water-use efficiency of producing wheat grain varies considerably but a reasonable estimate is about 1.3 kg/m<sup>3</sup> (Musick and Porter, 1990). Therefore, about 1.3 tonnes of wheat grain could be produced from the water harvested from a hectare of runoff area.

Although land treatment has a major impact on the runoff coefficient, the size of the contributing area and the intensity of the rainfall event are also major factors in determining the amount of runoff. A study in the Negev Desert (Ben-Asher, 1988) reported a runoff coefficient of 70 percent where the contributing area was 100 m<sup>2</sup>, but only about 15 percent where the contributing area was 10 000 m<sup>2</sup>. FAO (1991) showed a relationship between the amount of rainfall for a particular event and the runoff coefficient. That work showed a runoff coefficient of 35 percent when 50 mm of precipitation was received, but only 5 percent when 15 mm of precipitation fell. These values will change depending on the

PLATE 14

This simple rainwater-storage system ensures that clean water is readily available to the household (A. Conti)



surface treatment. Where the contributing area is covered with plastic or other material that is impermeable, the differences will become much smaller and in some cases the runoff coefficients can approach 95 percent.

## REDUCING EVAPORATION

Evaporation is a major cause of water loss in semi-arid regions. The goal of efficient water use in semi-arid regions should always be to maximize the percentage of annual precipitation used for transpiration by decreasing losses from runoff, evaporation and percolation (El-Swaify *et al.*, 1985). In most semi-arid locations, evaporation from the soil is the largest loss (Figure 8.) In addition to water loss by evaporation during fallow periods, there are significant losses during the crop-growing period. Water loss by soil evaporation during the growing season is highly dependent on the leaf area index (LAI). The LAI is the total area of green leaves per unit area of ground covered, usually expressed as a ratio (WMO, 1990). At a LAI of less than two, half or more than half of the evapotranspiration is evaporation from the soil surface (Ritchie, 1983). Evaporation from the soil surface can be as much as 20 percent even at a LAI of 3 or more.

For sorghum, Hanks, Allen and Gardner (1971) found about 36 percent evaporation from the soil surface at a leaf area index of 1.2. Using a computer simulation model, Stewart and Steiner (1990) estimated that 30–35 percent of the evapotranspiration for grain sorghum grown at a high soil-water level was lost as evaporation,

BOX 7

## Rooftop water collection for food security

### A South African case

Laying a thin cement surface around rural homes is effective in capturing rainwater and can feed into underground storage tanks. Roof water can be captured in the same manner, eliminating the need for gutters. With an annual rainfall of 500 mm, impermeable surfaces of 100 m<sup>2</sup> – approximately the area of the roof and lapa (paved area) of a modest-sized rural home – can yield 50 m<sup>3</sup> of water during South Africa's dry season. This is sufficient to irrigate a vegetable garden and contribute towards food security for poorer families. This method has the added benefit of providing relatively clean and sediment-free water (IWMI, 2003).

### Water-storage structures

Tanks may store water collected from ground surfaces, tin rooftops, greenhouses, springs and rivers. The stored water can be used for irrigating crops (supplementary, full irrigation or both), supplying water for livestock and household needs or any combination of these.

Depending on their size and type, water tanks may serve individual households, groups of them, schools, hospitals or the whole community. In general, larger tanks cost more than individual structures, but are cheaper per cubic metre of water stored. They are also more difficult to construct and manage. Although the use of plastic bags has proved useful in India, a balance between economy and durability should be considered when designing storage tanks.

An example of a cost-effective water-storage structure is the externally reinforced brick tank developed by the University of Warwick (United Kingdom). Supported by a packaging strap, this structure is able to withstand internal stresses. As a result, it requires less material in construction. Modern construction and design can also improve indigenous methods of water storage. For example, hand-dug wells can be lined with steel barrels, cement bricks or steel-reinforced concrete for greater durability (IWMI, 2003).

TABLE 4

**Factors governing the amount of runoff from a water-harvesting catchment**

Major factor	Associated factors
1. Rainfall	Rainfall intensity Rainfall duration Rainfall distribution Events of rainfall causing runoff
2. Land topography	Degree of land slope Length of run Size and shape of the catchment Extent of depressions and undulations of the catchment
3. Soil type	Soil infiltration rate Antecedent soil moisture Soil texture Soil structure Soil erodibility characteristics
4. Land-use pattern	Cultivated, uncultivated or partially cultivated Under pasture or forests Bare, fallow or with vegetation Soil- and moisture-conservation measures adopted or not Crop cultural practices adopted

Source: Adapted from Radder, Belgaumi and Itnal, 1995.

and that 40–45 percent was lost as evaporation under intermediate soil-water conditions. A major strategy for increasing yields in dryland regions should be to reduce evaporation losses during both the fallow period and the crop-growing season.

The land in the Great Plains of the United States of America was tilled repeatedly during fallow periods to control weeds so that soil-water levels would be increased for the subsequent wheat crop. However, these practices left the soil bare and caused a rapid decline in SOM, triggering extensive wind erosion during the

TABLE 5

**Water-harvesting efficiencies of surface treatments for enhancing runoff**

Surface treatment of the catchment	Water harvesting efficiency <sup>a</sup>
	(%)
1. Compacted soil surface	30–60
2. Removing the vegetation	7–21
3. Roaded catchment	24–41
4. Coating of bitumen on compacted soil	65–89
5. Sodium chloride	10–64
6. Sodium carbonate	35–71
7. Mixture of bentonite clay and sodium chloride	48–61
8. Bentonite clay	19–56
9. Asphalt	60–90
10. Asphalt fibreglass sheet	85–95
11. Asphalt roofing	52
12. Bitumen with kerosene soil	77
13. Concrete membrane	56–80
14. Low-density polyethylene sheet	60–85
15. Silicane and paraffin	50–80

<sup>a</sup> Percent of precipitation falling on catchment area harvested. Source: Modified from Radder, Belgaumi and Itnal, 1995



drought years of the 1930s: the infamous Dust Bowl, a major human-exacerbated ecological disaster (Stewart, Jones and Unger, 1993). In order to combat this problem, stubble mulching became widespread: pulling flat V-shaped sweeps or blades through the soil about 10 cm beneath the surface. This operation cuts plant roots and kills the weeds but does not invert the soil. Therefore, much of the crop residue is left on the surface as a mulch to protect against wind and water erosion and reduce evaporation loss. Even relatively small quantities of residues are highly effective in the control of both wind and water erosion (Plate 15). As a guideline, plant residues covering 30 percent of the soil surface will reduce both wind and water erosion by about 80 percent (Lafren, Moldenhauer and Colvin, 1981; Fryrear, 1985). Although stubble mulching was developed to address the wind erosion problem, it soon became evident that the mulch increased soil-water storage as well. This is attributed to increased infiltration as well as to reduced evaporation. The contribution of each of these factors will vary with specific conditions

Mulches left on the soil surface – or dust mulch by repeated ploughing under certain conditions as in India (Annex 2) – have proved effective in reducing evaporation during fallow periods. Other studies have also shown that leaving crop residues on the soil surface reduces evaporation and increases soil-water storage (Cornish and Pratley, 1991; Li Shengxiu and Xiao Ling, 1992; Smika, 1976). Unger and Parker (1976) showed that wheat stubble was about twice as effective in decreasing soil-water evaporation as grain sorghum stubble and more than four times as effective as cotton stalks. The differences resulted primarily from the physical nature of

the residues (hollow, pithy or woody), which affected the specific gravity and, hence, their thickness and surface coverage when applied at identical rates by weight.

Surface residues are most beneficial for reducing evaporation when several precipitation events occur over a period of a few days. This allows each successive precipitation event to wet the soil to a greater depth. Water stored at greater depths is less vulnerable to evaporation and, therefore, more likely to be available during the next cropping season.

Achieving a reduction in evaporation during the growing season is somewhat more complex than during a fallow period. Unger and Jones (1981) evaluated the effect of straw mulch during the growing season on growth, yield, grain quality, water use and water-use efficiency of grain sorghum. Sorghum responded more to the amount of soil water at time of seeding than to the presence of mulch during the growing season. A positive impact of mulch was found mainly on the plots with a low water level. The authors concluded that shading from the plant canopy largely substituted for the beneficial effect of mulch during the growing season. Therefore, the best strategy for increasing the transpiration portion of evapotranspiration is to establish a plant canopy as quickly as feasible, e.g. through narrower row spacing and higher plant populations. However, these practices can lead to lower water-use efficiencies when the harvestable product is grain because the soil water may become depleted prior to grain filling. This dilemma is faced by dryland crop producers in selecting the proper row width and plant density.

TABLE 6  
Estimated runoff coefficients and cost of runoff-inducement techniques

Treatment	Runoff coefficient (%)	Estimated life (years)	Cost (US\$ per 100 m <sup>2</sup> )
Catchment clearing	20–35	1–3	1–4
Surface smoothing	25–40	2–4	2–4
Soil compaction	40–60	2–3	6–10
Surface modification	70–90	3–5	10–20
Surface sealing	60–80	5–10	4–10
Impermeable cover	95–100	10–20	20–100

PLATE 15

Smallholder coffee farmers cover the ground with straw to preserve humidity, Malawi (A. Conti)



A better practice, particularly for summer crops such as grain sorghum, may be to choose cultivars with a shorter growing period. These can be seeded at a higher plant population, resulting in a more complete canopy at an early stage. Studies in the semi-arid Texas High Plains in the United States of America by Jones and Johnson (1997) suggest such a short-season, high-density strategy for dryland grain–sorghum production. Short-season hybrids have a lower genetic yield potential than long-season hybrids, but they have a higher harvest index and use water over a shorter period. This places less reliance on individual growing-season precipitation and more reliance on stored soil water to produce grain. Jones and Johnson (1997) stated that the short-season, high-density strategy for successful grain sorghum production in the Texas High Plains requires a soil profile with 125–200 mm of stored plant-available soil water and an anticipated growing season precipitation of at least 250 mm.

### INCREASING SOIL ORGANIC MATTER CONTENT AND FERTILITY

The primary repository of soil fertility is soil organic matter (SOM). A decrease in SOM is an indicator of declining soil quality because SOM is extremely important in all soil processes biological, physical, and chemical. It acts as a storehouse for nutrients, improves nutrient cycling, increases the cation-exchange capacity and reduces the effects of compaction. It builds soil structure increasing the infiltration and water storing capacity. It serves as a buffer against rapid changes in pH and an energy source for soil micro-organisms.

BOX 8

Growing sorghum plants in clumps to increase grain yield

Recent studies by Bandaru et al. (2006) have shown that growing grain sorghum in clumps of 3 or 4 plants instead of equally spaced plants can increase grain yield significantly under certain semiarid conditions.

In the southern Great Plains of the United States, stored soil water and growing season precipitation generally support early season growth but are insufficient to prevent water stress during critical latter growth stages. Growing plants in clumps compared to uniformly spaced plants reduces the number of tillers and vegetative growth. This preserves soil water until reproductive and grain-filling stages, which increases grain yield. There are marked differences in plant architecture of uniformly spaced plants compared to clumped plants. Uniformly spaced plants produce more tillers and the leaves on both the main stalk and tillers grow outward, exposing essentially all the leaf area to sunlight and wind. In contrast, clumped plants grow upward with the leaves partially shading one another and reducing the effect of wind, thereby reducing water use. In the studies by Bandaru et al. (2006), grain yields were increased by clump planting by as much as 100 percent when yields were in the 1000 kg/ha range and 25 to 50 percent in the 2000 to 3000 kg/ha range, but there was no increase or even a small decrease at yields above 5000 kg/ha.

An annual loss by decomposition of 1–2 percent of the organic matter in the surface 15 cm of cultivated soils is not uncommon. In some climates, the loss can be considerably higher. For example, Pieri (1995) summarized data from semi-arid regions of Africa and reported that on highly sandy soils, annual ploughing with application of fertilizers led to an annual loss of 5 percent or more in organic matter. Only practices with manure applications prevented a decline in SOM. The effect of ploughing by itself was less clear, but several of the reported studies indicated that ploughing increased the rate of decline. Pieri (1995) proposed that there

is a critical level for SOM dependent on the sum of the clay and silt contents. Where the SOM percentage falls below the critical level, the maintenance of soil structure becomes difficult. However, he disagreed with agronomists who argue that, as SOM is important in soil quality, the higher the SOM content, the better the soil. Pieri stated that it is fruitless to aim for a SOM percentage above the critical level in semi-arid Africa, where there are many other technical and economic constraints on crop performance. Most drylands soils have been depleted in SOM due to inappropriate cultivation, overgrazing and/or deforestation in the past, causing a decline in soil quality and emission of C into the atmosphere. There is great potential to increase the SOM of most dryland soils before such a critical level (equilibrium) is reached (Lal, 2002a).

One of the problems with crop production in drylands is determining whether there are favourable moisture interludes in the cycle of plant development when the soil cannot supply sufficient nutrients. Total yield and water-use efficiency can be increased where fertilizers can increase the net assimilation rate or growth in these periods without exhausting water at a faster rate. If fertilizers accelerate the rates of growth and water use, the yield and water-use efficiency will depend on the total supply of water and the status of the crop when the water supply becomes exhausted. Thus, accelerated water use through fertilization can be disastrous for grain crops if the soil water supply is exhausted and rainfall events do not occur in time for grain filling. This timing of water use, total water supply and plant development is much less critical for crops that are grown for their vegetative parts and do not need to complete their life cycle through seed production.

In studies of fertilizers and the efficient use of water, various authors in Kirkham (1999) concluded that any practice that increases dry matter production would lead to increased water-use efficiency. Exceptions are those cases where water greatly in excess of consumptive-use demands is essential in attaining that production, such as frequent irrigations after planting to establish small-seeded crops or leaching with irrigation water to remove soluble salts. The conclusion by Viets (1962) that increases in dry

matter production increases water-use efficiency is also reflected in the relationships in Figure 7, which show that cereal yields can be significantly different when the same amounts of water are used. Differences in yields occur when inputs are added to remove other constraints. However, it is important to note that the added inputs do not have a marked effect unless the water constraint is addressed (Kirkham, 1999).

Long-term agricultural experiments in Europe and North America indicate that soil organic matter and carbon are lost during intensive cultivation. Losses typically show an exponential decline following the early years of cultivation of virgin soils, with continuing steady losses over many years (Arrouays and Pélissier, 1994; Reicosky *et al.*, 1995); Reicosky, Dugs and Torbert, 1997; Rasmussen *et al.*, 1998); Tilman, 1998; Smith, 1999; Pretty and Ball, 2001). It has also been established that SOM and soil carbon can be increased to new higher equilibria with sustainable management practices. A wide range of long-term comparative studies show that organic and sustainable systems improve soils through the accumulation of organic matter and soil carbon, with accompanying increases in microbial activity, in various locations: the United States of America (Lockeretz, Shearer and Kohl, 1981; Wander, Bidart and Aref, 1998; Petersen, Drinkwater and Wagoner, 2000); Germany (El Titi, 1999; Tebrügge, 2000); the United Kingdom (Smith *et al.*, 1998; Tilman, 1998; Scandinavia (Kätterer and Andrén, 1999); Switzerland (FiBL, 2000); New Zealand (Reganold, Elliott and Unger, 1987; Reganold *et al.*, 1993); only a small number of studies have been undertaken in the tropics (Chander *et al.*, 1997; Post and Kwon, 2000).

The importance of soil organic matter is difficult to overemphasize, particularly in semi-arid regions and its maintenance is clearly a major constraint on the development of sustainable agro-ecosystems. Despite the many proven benefits of SOM, its management and recycling in an intensified, modern agro-ecosystem must necessarily revolve around two fundamental characteristics:

- the on-farm availability of organic material;
- and the economic incentive for conserving and recycling organic matter.

Perhaps the two most important practices for maintaining SOM are to minimize soil disturbance and to apply organic (animal, human and vegetal) wastes. Other practices that lead to increased yields are also important, because more carbon will be added to the soil from increased root production and crop residues (Plate 16). The high demand for crop residues in many developing countries for fuel and animal feed makes it particularly challenging to maintain SOM. This problem is likely to be further exacerbated in future as the new demand for residues to produce second generation biofuels develops. Where feasible, it is better to have animals graze crop residues *in situ* so that the manure is distributed over the area, rather than to remove the residues for feeding off-site. When it is necessary to remove the crop residues for use as livestock feed (i.e. in lot or zero grazing systems), every attempt should be made to return the manure produced to the land. Otherwise, the SOM content will continue to decline and may reach a level where the long-term sustainability of the soil-resource base becomes threatened.

Most indigenous soil- and water-conservation practices in drylands have tillage as their centrepiece. Since the early 1960s, however, scientists and farmers have been developing forms of conservation tillage to:

- reduce production costs and increase profit margins for farmers;
- reduce runoff and associated losses of soil, water, seeds, and applied inputs and organic matter;

- reduce wind erosion and wind erosion air quality degradation;
- improve environment for root development, including better availability of plant nutrients in the root zone, better infiltration and water-holding capacity of soils, and reduced amplitude of day-to-night temperature ranges;
- increase efficiency of use of the available water;
- reduce the amount of fossil fuels used in growing food; and
- maintain or enhance soil organic matter.

Conservation tillage and conservation agriculture are often used as umbrella terms commonly given to no-tillage, minimum tillage and/or ridge tillage, to denote that the inclusive practices have a conservation goal of some nature (Baker *et al.*, 2007). Usually, the retention of at least 30 percent ground cover by residues after seeding characterizes the lower limit of classification for conservation tillage or conservation agriculture, but residue levels alone do not adequately describe all conservation tillage or conservation practices and benefits.

Conservation agriculture (CA) is specifically defined by FAO as a system that aims to achieve sustainable and profitable agriculture and subsequently aims at improved livelihoods of farmers through the application of the three CA principles: minimal soil disturbance, permanent soil cover and crop rotations (FAO, 2007). In reality, some conservation systems do not always employ all three of these principles. Studies have shown that successful implementation of these principles promotes infiltration of rainwater, reducing or eliminating runoff (blue water) and erosion, also reducing evaporation (white water) and lowering soil surface temperatures – conditions for more effective for soil and water conservation (Lal, 1997; FAO, 2004). With time under CA, soil life assumes the functions of human / mechanical soil tillage, loosening the soil and mixing the components. The adoption of conservation farming has generally been slow – attributed primarily to the fact that the routine of tillage in conventional agricultural systems, whether by hand, ox- or tractor drawn plough, is so heavily ingrained in the culture of arable farming communities.

PLATE 16

**Smallholder farmers incorporate crop residues in the soil to improve soil fertility, Malawi (A. Conti).**



**Plate 17**  
**As a farmer ploughs, serious erosion**  
**eats away the land.**



Research from several countries shows significant improvements in crop yields and reduced soil erosion, also lowering peak labour demand and reducing labour requirements after the introduction of tied ridging or pitting to increase infiltration, followed by the adoption of zero- or minimum-tillage (direct-planting) systems (Kaumbutho and Simalenga, 1999). Conservation agriculture is a promising approach for redirecting the components of the water balance in favour of infiltration and consequently crop transpiration (green water) and production (WOCAT, 2007). Experience has shown that CA systems achieve yield levels as high as comparable conventional agricultural systems, but with less fluctuation due for example to drought, storms and floods. CA therefore contributes to food security and poverty reduction, reducing the risks for the communities (health, living conditions and water supply) and also the costs for the State (less need for road maintenance and emergency assistance).

The general population of the district, state or river basin also gain considerable benefits from positive externalities of widespread conservation agriculture (FAO, 2002). These include: less downstream sedimentation; more regular river flows; aquifer recharge; reduced air pollution; increased carbon sequestration; and conservation of terrestrial and soil-based biodiversity.

Soils are the largest carbon reservoir of the terrestrial carbon cycle. The quantity of C stored in soils is highly significant on the global scale; soils contain about three times more

C than vegetation and twice as much as that which is present in the atmosphere (Batjes and Sombroek, 1997). Soils contain 1 500Pg of C to 1m depth and 2 500Pg of C to 2m (1Pg = 1 gigatonne); vegetation contains 650Pg of C and the atmosphere 750Pg of C.

Conservation agriculture, zero and low tillage agricultural systems in all farming systems provide a sink for the growing atmospheric concentrations of carbon dioxide (CO<sub>2</sub>) which are driving climate change (Lal, 1997; Schlesinger, 2000; FAO, 2004; Stern, 2006). This benefits land users directly, as they improve the organic matter status of their soils, improving fertility and water storing

#### BOX 9 Effects of tillage on soil

Tillage results in a rapid decline in SOM, particularly in hot regions. Tiessen, Cuevas and Chacon (1994) reported that soil carbon contents in Canadian prairie soils had decreased by about 50 percent as a result of 65 years of cultivation. In contrast, only 6 years of cultivation in a Brazilian semi-arid thorn forest reduced the soil carbon content by 40 percent (Wood, Sebastian and Scherr, 2000). Nevertheless, the plough remains the symbol of agriculture, and tilling the soil has been hailed as the most effective way of controlling weeds and improving soil fertility. In the early years of cultivation, soil fertility may be adequate because the decomposition of SOM releases all the nutrients required for plant growth. However, these nutrients are nothing more than the debris of decomposed SOM. Unless the fallow period is long enough, the soil fertility declines rapidly in dryland regions following cultivation. At the same time, the soil physical properties deteriorate and make the already limited water less effective. The hazards of wind and water erosion are also increasing. Growing demographic pressure is causing persistent land degradation. As a result, farmers in many areas may be experiencing agricultural drought even when there is no meteorological drought, with crops suffering from a scarcity of plant-available soil water even when there is adequate precipitation.

capacity, resulting in more reliable crop yields. Often without being aware of it, CA practitioners are contributing to mitigating the effects of GHG emissions from the burning of fossil fuels. Lal (2004) calculated that an increase of 1 ton of soil carbon pool of degraded cropland soils may increase crop yield by 20 to 40 kilograms per hectare (kg/ha) for wheat, 10 to 20 kg/ha for maize, and 0.5 to 1 kg/ha for cowpeas. As well as enhancing food security, carbon sequestration has the potential to offset fossil fuel emissions by 0.4 to 1.2 gigatons of carbon per year, or 5 to 15 percent of the global fossil-fuel emissions.

In the case of drylands, the lack of water severely constrains plant productivity and affects the accumulation of C in dryland soils (FAO, 2004). Consequently dryland soils contain relatively small amounts of C (between less than 1 percent and less than 0.5 percent (Lal, 2002b)). The organic matter content of dryland soils will rise with the addition of biomass to a soil which has previously been depleted due to land use change (e.g. conversion from natural vegetation to arable). Although the rate at which carbon is sequestered is low in drylands compared with soils of temperate regions, the potential offered by drylands to sequester C is large, not only because of the large geographical extent, but because historically, soils in drylands have lost significant amounts of C and are far below their critical level (FAO, 2004 and Oldeman *et al.* (1991).

Although conservation agriculture and other types of conservation systems offer substantial benefits, adoption has been slow. FAO (2001b) reported that conservation agriculture was being practised on about 45 million ha in 2000, or about 3 percent of the 1 500 million ha of arable land worldwide. The transformation from conventional tillage to conservation agriculture requires farmers to acquire considerable management skills and involves investment in new or modified equipment or tools. It also requires a higher level of management, and perhaps most important, a change in the mindset of farmers.

## THE IMPORTANCE OF CROP AND CULTIVAR SELECTION

Water- and soil-management strategies should be accompanied by using appropriate crops and cultivars with optimal physiology, morphology and phenology to match local environmental conditions. Breeding and selection for improved water-use efficiency and the use of genotypes best adapted to specific conditions can improve soil-water use and increase water productivity (Studer and Erskine, 1999).

An important approach to increasing the efficiency

### BOX 10

#### Early sowing of chickpea

In the Mediterranean region, rain falls predominantly in the cool winter months of November–March. Traditionally, chickpea is sown in late February and early March. As a consequence, the crop experiences increasingly strong radiation and a rapid rise in temperature from March onwards. This causes the rate of leaf area development to increase with consequent high evapotranspiration. This period of high evaporative demand occurs at the end of the rainfall when the residual soil moisture is inadequate to meet the evaporative demand. Therefore, the crop experiences drought stress during late vegetative growth and reproductive growth, resulting in low yields. The replacement of traditional spring sowing with winter sowing is possible but only with cultivars possessing cold tolerance and resistance to key fungal diseases [For chickpea, specifically breeding is for tolerance to *Ascochyta* Blight (Singh and Ocampo, 1997; Studer and Erskine, 1999).]

The average gains in seed yield from early sowing chickpea over three sites and ten seasons is 70 percent, or 690 kg/ha, which translates into an increase in water-use efficiency of 70 percent (Erskine and Malhotra, 1997). In 30 on-farm trials comparing winter with spring chickpea in north of the Syrian Arab Republic, the mean advantage of winter sowing in seed yield and water use efficiency was 31 percent (Pala and Mazid, 1992). Currently, an estimated 150 000 ha of chickpea is winter-sown in the West Asia and North Africa regions.

of water use is to change both water-management practices and cultivar concurrently. This allows a considerable increase in productivity. Seasonal shifting, i.e. the development of crop varieties that can be grown in winter under lower evaporative demand, represents an additional challenge for breeders seeking to use scarce water more efficiently as traits such as winter hardiness and disease resistance have to be improved. Early and complete canopy establishment to shade the soil and reduce evaporative loss from the soil surface can significantly improve the water productivity of rainfed crops in Mediterranean conditions and also that of summer-rainfall crops over much of the semi-arid tropics (Cooper *et al.*, 1987 and Oweis *et al.*, 2001).

An alternative approach, particularly appropriate for subsistence smallholders in drylands is to resume growing the wider range of more traditional grain crops and legumes, which are better adapted to dry land conditions, not restricting themselves to the small range of varieties of crops which have become ubiquitous in the late twentieth century (wheat, barley, sorghum, maize) and legumes (chickpea and clovers)

Agrobiodiversity is a vital subset of biodiversity (CBD, 2007 and FAO, 2005). Sources of stresses are numerous in the drylands (drought, insect attacks, diseases, high temperatures, off-season rain). One of the major ways farmers can minimize risk is by growing a diversity of crop species and varieties.

The implications of the rapid reduction in agrobiodiversity during the twentieth century (particularly post Green Revolution) have been profound, increasing the risk of harvest failures due to drought, disease and / or pests. Raising awareness of the importance of local agrobiodiversity will contribute to reducing the risk of crop failure in the coming decades.

## ROLE OF INDIGENOUS AND INTRODUCED PRACTICES

Local farmers are the key individuals with responsibility for improving soil and water conservation and management in developing countries. These small-scale farmers are highly diverse. Even within small communities, individual

farmers have a wide range of circumstances, including their needs, priorities, availability of resources and also preferences. Farmers each have a wealth of knowledge about their crops, their soils, their farming environment, also diverse socio-economic conditions. They use this knowledge as the basis not only for making decisions and communicating with one another, but also in many cases as the basis for innovation. Small-scale farmers are keen observers and conduct experiments on their own (Reij and Waters-Bayer, 2001). Policy-makers and scientists must understand and appreciate the depth of local knowledge before they can communicate with the farmers to acquaint them with new or improved technologies. Large-scale top down approaches (transfer of technology models) to development have repeatedly been shown not to succeed, often as they are too costly for small-scale farmers to implement – or they do not take into account local factors (Reij and Waters-Bayer, 2001). Farmer field schools which encourage learning-by-doing are increasingly proving successful to help smallholders learn new information, particularly in the field of integrated pest management and conservation agriculture (Van de Fliert, 1993; Feder *et al.*, 2004; Simpson and Owens, 2002). Understanding and trust between all parties must be established before farmers can be expected to test, adapt and adopt new or improved technologies.

Indigenous practices refer to local practices (Plate 18), as distinct from interventions initiated

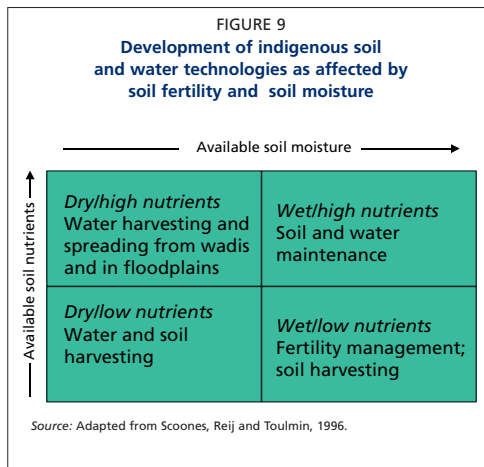
PLATE 18

**A farmer clears a canal to ensure water flow through a falaj system in Oman. The falaj system in the Al-Jauf region dates back 2 500 years**



from outside (Scoones, Reij and Toulmin, 1996). However, many practices regarded as indigenous today may have been derived from elsewhere in the past (Oweis *et al.*, 2004). They become indigenous once they have been adapted to fit local conditions, widely accepted by local farmers and used for many years. In essence, these practices become part of the local culture and are not easily changed. Introduced practices are often specified in technical manuals and extension handbooks with precise dimensions and design requirements. Indigenous practices are much more flexible. Flexibility is important, as field topography and other biophysical and socio-economic conditions vary from site to site.

For the development planner and project administrator, the use of an off-the-shelf technical package might be appealing. However, when new technologies are introduced, and particularly where they are imposed, problems arise. The reasons for problems vary widely from setting to setting. Scoones, Reij and Toulmin (1996) found that where land is in plentiful supply, or where the cultivator can easily move into other fields of economic activity, there may be little long-term interest in maintaining soil fertility. Areas with high population densities and few options outside agriculture often had elaborate soil- and water-conservation structures. In contrast, the level of labour investment for water harvesting and other practices was far lower in areas with low population density. In many cases, the tasks related to indigenous practices were divided



according to gender and introduced practices may interfere with this balance (Scoones *et al.* 1996) and IWMI, (2006).

Figure 9 summarizes the development of indigenous soil- and water-management practices. Where both soil moisture and soil fertility are low, indigenous practices focus on both soil management and water harvesting. Where soil moisture is low but fertility is high, the focus is on water harvesting. However, in both cases, there are few or no inputs other than labour. As soil moisture becomes less of a constraint, the management focuses more on fertility and soil and water maintenance. Scoones, Reij and Toulmin (1996) also compared the characteristics of indigenous and introduced soil- and water-

**TABLE 7**  
**Characteristics of indigenous and introduced conservation practices**

Characteristics	Introduced practices	Indigenous practices
<b>Designed by</b>	Engineers and development planners	Local farmers
<b>Designed for</b>	Soil conservation	Multiple, depending on setting (including soil/water harvesting, conservation, disposal)
<b>Design features</b>	Standardized in relation to slope features	Flexible, adapted to local microvariation
<b>Construction</b>	One-time	Incrementally (fitting with household labour supply)
<b>Labour demands</b>	High	Variable, generally low
<b>Returns</b>	Long-term environmental investment	Immediate returns
<b>Project setting</b>	Large-scale, campaign approach; food-for-work / cash-for-work/ employment-based safety-net programmes, etc.	Longer-term support to indigenous innovation; participatory research and farmer-to-farmer sharing

Source: Adapted from Scoones, Reij and Toulmin, 1996.



conservation practices (Table 7), indicating that soil- and water-conservation practices often face serious constraints.

Kerr and Sanghi (1992) reviewed indigenous soil- and water-conservation practices in six regions of India's semi-arid tropics and found that these were generally preferred to introduced practices (Box 11). The indigenous practices evolved in different ways from place to place in response to local agro-ecological and economic conditions. Three factors were common among all locations:

- Firstly, the designs of indigenous practices reflected the relative availability and opportunity costs of different agroclimatic factors and resources, including materials, human labour, animal power and cash.
- Secondly, practices developed within the constraints of small, fragmented farms in accordance with farmers' preferences to invest in soil and water conservation individually or in cooperation with an adjacent farmer rather than in large cooperative groups.
- Thirdly, economic factors determined adoption patterns.

Investments in soil and water conservation and management are one among a range of economic concerns. Farmers assimilate available information in deciding how their time and money can be spent most productively. Their opportunities and constraints are not identical, so the same activity is not equally profitable for all farmers. Often, soil- and water-conservation practices introduced by outside groups or organizations have a single objective. In order to meet this objective, technologies are introduced with designs to conserve the maximum amount of soil and water. In contrast, farmers have multiple objectives that may include soil and water conservation.

One indigenous practice relating to soil and water conservation, water harvesting and water management is that of using "qanats". This is an irrigation system that was developed in Persia some 2 000 years ago and then spread to central Asia, China and North Africa. This indigenous practice takes advantage of the rainfall and groundwater resources in arid regions bringing water resources to the surface by gravity through carefully designed underground canals. Qanats are

#### BOX 11

##### Using traditional water conservation and harvesting techniques

Contour bunds are an example cited by Kerr and Sanghi (1992) illustrating a conflict between indigenous and introduced practices. Soil scientists and engineers recommend that bunds be located on the contour so that runoff water is spread evenly. The bunds can reduce runoff, increase infiltration, and divert excess runoff to a central waterway. Most dryland farmers in India have rejected this practice because they want the bunds to conform to field boundaries, which rarely correspond to contours.

Li Shengxiu and Xiao Ling (1992) discussed many indigenous soil- and water-management practices in the drylands of China. The most prominent practices included terracing, frequent shallow cultivation for water conservation, and soil-fertility management. In Gansu Province, "stone fields" are used for growing cereals and fruit trees in an area with an annual precipitation of about 200 mm. This water-conservation practice is centuries old. It involves placing stones on the soil surface to drastically reduce evaporation from the soil surface and to collect dew condensing on the stones and flowing to the soil below during the night. This practice is highly labour-intensive and occurs mainly in areas where subsistence farming is a way of life.

still counted as one of the main ways of procuring water for irrigation and agricultural development as well as drinking-water in the drylands and desert areas of the Islamic Republic of Iran (Farshad and Zinck, 1998) and Afghanistan. However, in most cases, qanats are more than just a way of using groundwater. They represent a unique and integrative system illustrating the use of indigenous knowledge and wisdom in sustainable management of land and water resources. In North Africa and the Sahara, many oases are developed by qanat systems called foggara.

#### COMBINING MODERN WITH TRADITIONAL TECHNOLOGIES

Traditional rainwater-harvesting agriculture can be a valuable practice in increasing crop productivity in the semi-arid region of the Loess Plateau in

China. However, due to the lack of detailed data on precipitation resources in the region, there have been some difficulties in its development there.

In one study (Hong Wei *et al.*, 2005), based on the precipitation data in the last 40 years and topographical maps at 25 observation stations in and around Dingxi County, Gansu Province, China, raster digital elevation models and average annual precipitation databases in the study areas were established using geographical information systems (GISs). By means of interpolation approaches, statistical models and a comprehensive approach including nine methods (inverse distance weighted, ordinary Kriging, Thiessen polygon, multivariate regression, etc.), the spatial and temporal changes in annual precipitation were calculated and analysed comparatively. The annual average precipitation in Dingxi County calculated by the comprehensive approach is 420 mm, and the water deficit of spring wheat is about 226 mm. Therefore, rainwater-harvesting agriculture is feasible in the study area if appropriate harvesting technologies are applied. The annual average precipitation information system, established by raster precipitation spatial databases using optimized methods, can calculate promptly the total quantities and the spatial changes in precipitation resources on any scale in the study areas. This has an important role in runoff simulation, engineering planning, strategy development, and decision-making as well as water management in rainwater-harvesting agriculture.

### SUPPLEMENTARY IRRIGATION IN SEMI-ARID REGIONS

The relationship between grain yield and seasonal evapotranspiration shown in Figures 10 and 11 illustrates why supplemental irrigation is so effective in semi-arid regions. There is usually sufficient precipitation to meet the threshold value required for grain production and to produce some grain (Oweis *et al.* 1999). Therefore, additional water added by irrigation can result in a direct increase in grain yield. The focus of any irrigation system should be on maximizing the evapotranspiration component with added water and minimizing losses such as runoff and deep percolation. This is more difficult under semi-arid conditions than under arid conditions because the rainfall in semi-arid regions is more unpredictable and often

FIGURE 10  
Relationship between cumulative transpiration and biomass, and between cumulative evapotranspiration and grain yield

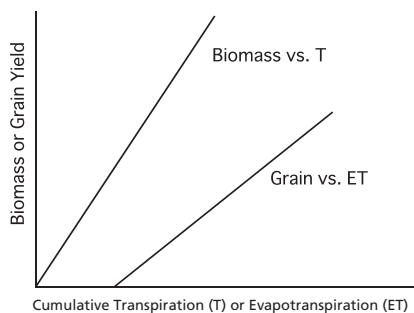
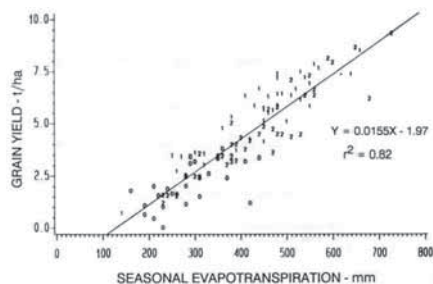


FIGURE 11  
Relationship between yield of grain sorghum and seasonal evapotranspiration



Source: Stewart and Steiner 1990

ranges from less than half to more than twice the average. Large rainfall events, particularly soon after irrigation, can result in large losses through surface runoff and percolation.

When relatively small amounts of irrigation water are added to grain crops grown under dryland conditions, most of the water will be used for evapotranspiration (Howell, 1990). This is because the soil will be generally dry, so the potential for runoff or percolation of the added irrigation water will be small. However, as more irrigation water is applied, the soil becomes wetter and the potential for losses increases. This is one of the difficulties with efficiently utilizing irrigation

water to supplement precipitation. When water resources are limited, it is difficult to determine how much area should be irrigated as a fixed amount of water can irrigate a larger area during a wetter year than during a drier year. Deciding on how much land should be irrigated is critical where water-sensitive crops such as maize are grown. Attempting to irrigate too much land can lead to a water deficiency during a critical growth period such as tasselling (Macartney *et al.* 1971; Rhoads and Bennett, 1991; Oweis, 1997). At the other end of the spectrum, allocating sufficient water to an area so that there will be adequate water for a very high yield even in years of lower than average precipitation can also result in low water-use efficiencies.

Another important factor for grain crops is the harvest index: the ratio of grain weight to the weight of the total above-ground biomass.

Although there are no strategies that can eliminate all these complexities, an understanding of soil–plant–water relationships, precipitation probabilities, and hydrologic characteristics can greatly improve the efficient use of limited water resources for supplemental irrigation. The availability and cost of required infrastructure is perhaps the most important consideration for supplemental irrigation. Even though small amounts of irrigation water can often significantly improve total water-use efficiency, the cost of providing the necessary infrastructure may prevent its use.