Sustainable Water Management in Smallholder Farming

Theory and Practice

Sara Finley

CABI

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Contents

Part 1 Theoretical Foundations of Water Management in Agriculture

Preamble to Part 1

The Scope of this Book

This book provides an introduction to the theoretical foundations of agricultural water management, and presents a range of basic techniques for promoting efficient water use on farms. Subjects covered include crop water requirements, soil and water conservation, rainwater harvesting, conservation agriculture, supplementary irrigation, and more. The book provides a practical, as opposed to an academic, approach; it is hoped that farmers' groups, extension agents, students and non-governmental organizations (NGOs) can use it as a starting point for continued study. The wide variety of climate and farm types encountered across agricultural areas means that concepts presented are necessarily broad; space limitations prohibit detailed discussions of specific crops, soil types, or climate zones. The information provided here is intended as a generalized practical guide to a suite of techniques that can be adapted according to each farm's objectives, resources, climate, and crop.

The methods presented in this book are most applicable to agricultural projects that fall into the 'smallholder' category – that is, small farms with little or no mechanization. Though some information about partial irrigation is provided, the focus is primarily rainfed farms in climate zones characterized by overall rainfall deficits or frequent dry spells. While water is crucial for all forms of agricultural activity, this publication addresses only the soil-based cultivation of field crops.

The Importance of Water

Water is the lifeblood of the earth, and is vital to the health of humans, animals, plants and soils. Living things depend on water not just for the hydration it provides, but also for the nutrients and minerals that it carries with it. The quantity and quality of water available to a given population is closely tied to the quality of life it enjoys, with direct effects on education, health, economic well-being and personal dignity. Clean water is also fundamental to maintaining the health of natural ecosystems upon which all human activities depend.

In agriculture, water provides the basic elements required for photosynthesis and aids in transporting essential nutrients and minerals from the soil to the plant. Water delivery is a balancing act: the goal is to provide plants with sufficient moisture while ensuring adequate drainage so as not to saturate the soil. Because water can sometimes be difficult to access and its availability can fluctuate over time, effective water management is critical for success in agriculture.

Water and Agriculture: the Global Outlook

International experts agree that we are now entering an era of global water crisis.[1] The combined effects of growing demand, declining quality, and a changing climate have exerted a degree of pressure on water supplies that can no longer be sustained without consequence. The result has been a combination of widespread shortages, intensified conflict over access to water supplies, and a rise in occurrence of water-borne illnesses.

Despite global efforts to increase access to this precious resource, *water scarcity*, where water demand exceeds availability, is widespread and getting worse. Already, the United Nations estimates that 700 million people around the world suffer from water scarcity, and this number is expected to grow rapidly as pollution worsens and limited water supplies come under increased stress.[2] By the year 2025, nearly 2 billion people – about one-third of the current world population – are expected to be living in conditions of absolute water scarcity.[3] For some, this scarcity is related to physical water shortages in the environment, while for others the scarcity is economic, wherein personal incomes restrict the ability to access water reserves. Figure P1.1 shows the distribution of water-scarce regions in the world as identified in the International Water Management Institute's (IWMI) 2007 report *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*.[4]

Farming is both the cause and a victim of water shortage situations around the world. Globally, agriculture accounts for a full 70% of freshwater withdrawals, and this number reaches over 90% in most developing countries.[5] At the same time, there is urgent need to improve the productivity of agriculture, especially in developing nations where the number of hungry and malnourished people is increasing. Because it will be impossible to increase food production without also intensifying agricultural water use, the critical challenge lies in improving water use efficiency on a large scale.[6] For these reasons, water management for agriculture is now a central priority for development agencies and policy makers alike.

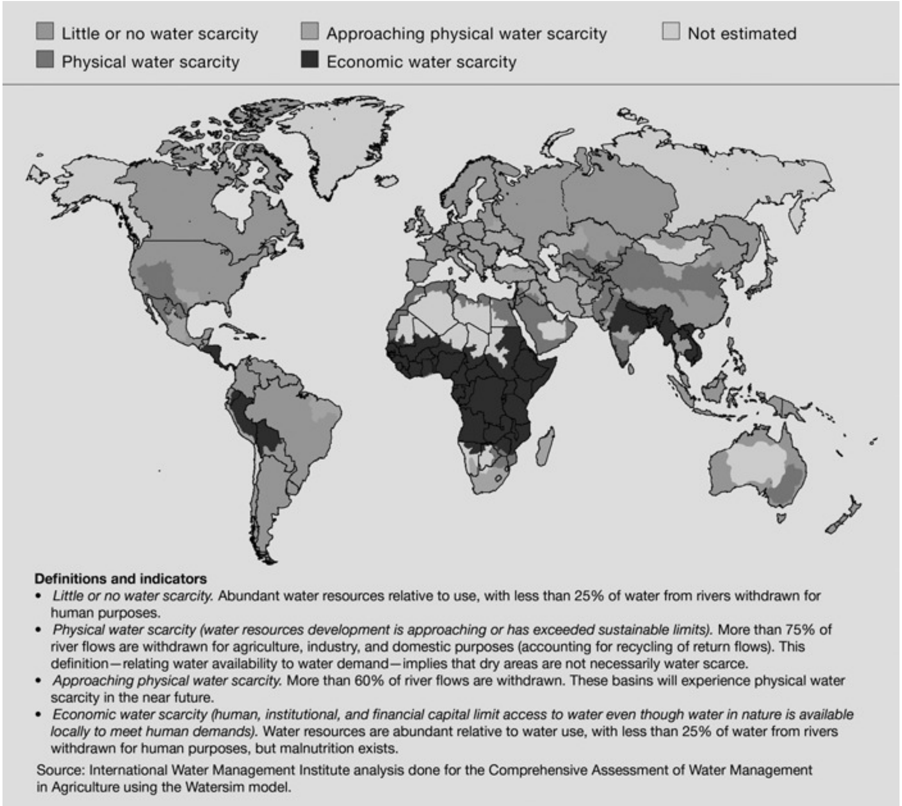

Fig. P1.1. Areas of physical and economic water scarcity. Reproduced with permission from the International Water Management Institute (IWMI), 2007.[4]

The first section of this book aims to introduce key concepts involved in water management for agriculture (Chapter 1), identify the general objectives of water management practices (Chapter 2), and provide the theoretical foundation of the relationships between soil and water (Chapter 3), and plants and water (Chapter 4). The last chapter in this section provides an outlook of the trend toward increased climate variability (Chapter 5), a topic that will become more and more relevant to farmers in the context of accelerating global climate change.

References

1 International Business Times, 2015. Catastrophic Global Water Crisis Looming Large, UN Warns. Available at: http://www.ibtimes.com/catastrophic-global-water-crisis-looming-large-un-warns-1854622 [Accessed November 5, 2015].

2 United Nations (UN) Water, International Decade for Action 'Water for Life' 2005–2015. Focus Areas: Water Scarcity. *un.org*. Available at: http://www.un.org/waterforlifedecade/scarcity.shtml [Accessed November 6, 2015].

[3] Ibid.

[4] Reproduced with permission from Comprehensive Assessment of Water Management in Agriculture, 2007. *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. London: Earthscan, and Colombo: International Water Management Institute.

[5] United Nations (UN) World Water Assessment Programme, 2014. The United Nations World Water Development Report 2014: Water and Energy. Paris: United Nations Educational, Scientific and Cultural Organization (UNESCO).

[5] Comprehensive Assessment of Water Management in Agriculture, 2007. *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. London: Earthscan, and Colombo: International Water Management Institute.

1 Key Concepts

The Water Cycle

Water exists in a variety of forms and on a number of levels in the ecosystem. *Surface water* flows in rivers, lakes and swamps, while *groundwater* flows underground through *aquifers* found at various depths within the soil and rock layers of the subsurface. Water stored in the top layers of surface water bodies, soils, and the ocean evaporates when heated by the sun. Evaporated water becomes *water vapor*, which makes the air humid, and vapor trapped in clouds will condense to become rain under the right conditions. When rain falls, a portion is absorbed into the soil, where it will either infiltrate toward groundwater aquifers or remain in reserve as soil moisture. The remaining rainfall will run off the surface of the land, flowing downhill into lakes and rivers and eventually the ocean. Water that moves through plants from the soil will ultimately be transpired into the air, becoming vapor once again. Figure 1.1 outlines the water cycle.

Water Distribution

Of all the water that exists on earth, 97.5% is saline, contained in oceans and inland saltwater seas. Of the remaining 2.5% that is freshwater, most (69%) is locked up in inland glaciers or icebergs on the ocean.[1] This leaves only a fraction (less than 1%) of the earth's water supplies in surface or groundwater available for human use. This tiny portion must then be partitioned among a diversity of functions in order to support human activities, economic development, and the natural environment.

Global water reserves are far from being equitably distributed. Water supplies vary widely among continents, within countries, and at the regional scale. The precise hydrological conditions of a given region will depend on both its

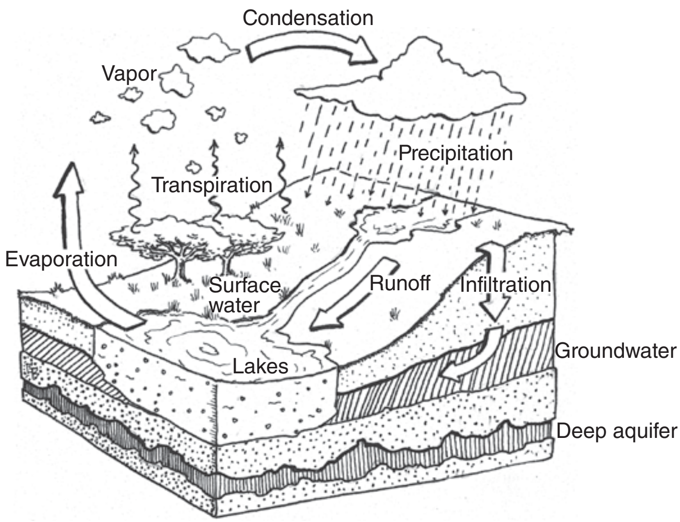

Fig. 1.1. The water cycle.

global location and its precise position in relation to local water reserves, including groundwater aquifers, surface water bodies, and the ocean. The presence of water in surface and groundwater reserves is in turn influenced by average rainfall values and the seasonality of that rainfall, as well as by topography and soil type. In each context, the availability of water to meet the demands of a given population will depend on both hydrological conditions and on a range of socio-political factors that affect its distribution among competing domestic, agricultural and industrial uses.

Current trends in water availability

While the total quantity of water present on earth does not change, the *availability* of water at any given time in a specific location can be highly variable. Rivers, lakes, soils and groundwater are natural water storage reservoirs, and their levels can change rapidly in response to human and environmental factors. Three variables in particular can affect the availability of water: (i) demand; (ii) climate patterns; and (iii) quality.

Demand

Many lower-income countries are currently experiencing significant population expansion, as well as rapid urbanization. Water is a limited resource, so the amount of water available per person declines as population pressure mounts. Water supplies must be divided among the competing demands of industry, human settlements, and agriculture, while leaving enough behind to maintain the health of the natural environment. The intensification of one or more of these water demands can lead to shortage situations even in areas where water resources have historically been sufficient. This effect is compounded by the fact that growing economies will continue to consume larger volumes of water as they expand.

Climate patterns

It is now internationally recognized that we are living in an era of accelerating global climate change.[2] The effects of climate change on water resources are manifold. In generalized terms, it is now expected that variations in the pace and rhythm of the hydrological cycle will lead to heightened unpredictability in rainfall patterns and distribution. On the ground, this translates to an increase in the frequency and intensity of climatic extremes, especially droughts and floods.[3]

Increased variability in rainfall patterns represents a special challenge for farmers, who use the timing of rains to plan for the production of crops and livestock. The Intergovernmental Panel on Climate Change (IPCC) has predicted that variations in rainfall patterns could reduce the productivity of rainfed agriculture by as much as 50% in some regions.[4] Augmented evaporation and plant evapotranspiration caused by rising temperatures are expected to negatively impact stream flow and reduce soil water holding capacity. These factors combine to diminish the capacity of local environments to provide a buffer against drought. At the same time, the looming threat of flooding and water scarcity impedes farmers' ability to plan for future harvests. In the decades to come, water shortages and flooding will be some of the most visible effects of global climate change.

Quality

Even in areas with abundant water resources, human and environmental factors can render water unusable by degrading its quality beyond acceptable levels. The most prevalent causes of water pollution are agricultural runoff, untreated sewage, industrial discharges, and improper waste disposal. Unfortunately, water pollution is now rampant in most parts of the world and little is being done to control it. Water pollution is currently the most significant factor limiting the availability of drinking water worldwide, and drinking contaminated water is itself among the leading causes of illness and death.[5]

In agriculture, runoff water contaminated with pesticides, fertilizers and sediments can have a significant environmental impact on both land and water resources. Agricultural pollution not only affects downstream users, but can also lead to an irreversible contamination of local groundwater and surface water supplies, compromising the future viability of the entire agricultural region.

Water in Agriculture

Plants and water

Water plays multiple roles in plant development. The H_2O (water) molecule is an important source of hydrogen and oxygen necessary for photosynthesis and biomass production. It also serves as the plant's transport mechanism for moving sugars, minerals and nutrients from place to place. Water is in constant movement through a plant, moving from root to leaf, where it is released as vapor in the process of transpiration (see Fig. 1.2). As it moves upwards toward the leaves it carries dissolved minerals and nutrients necessary to support metabolic functions and delivers them to different parts of the plant. If plant roots no longer have access to available water, transpiration will stop temporarily and the chain of movement will come to a halt, slowing photosynthesis and plant development. This is the plant's natural defense mechanism, allowing it to retain the water already contained in its tissues. However, after some time without new water inputs the plant will show signs of stress, wilt, and eventually die. Plants that develop under water stress conditions will have smaller leaves and stems, and produce fewer and smaller fruit, than those grown in optimal moisture conditions.[6]

A balance of water and drainage is essential for maintaining plant health. Soil drainage is important because it allows for a supply of air and the oxygen it contains to the plant's root system. Like water, oxygen is absorbed through the roots and moves upwards through the plant. If soil is saturated with too much water, air is not available to the root system and the plant will suffer from something like asphyxiation, causing its development to stop. Over-watering and/or poor drainage can cause root damage and can lead to root rot. Signs of excess water include drooping, leaf drop and brown spotting. Plants grown under conditions of excess water will be small, weak, and produce few fruits.

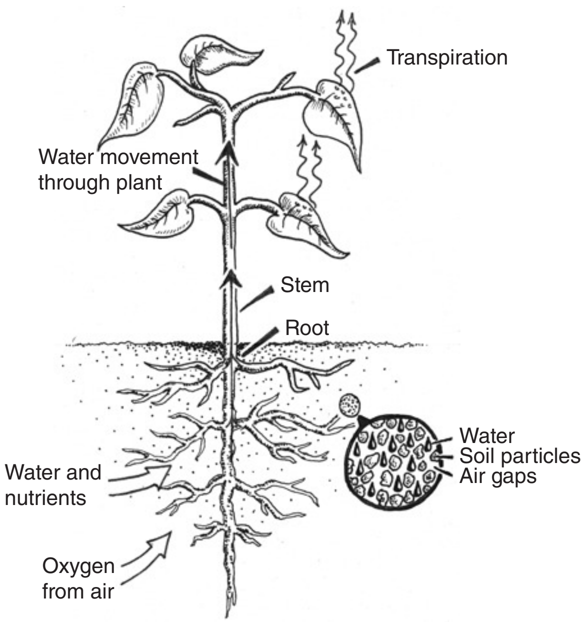

Fig. 1.2. Water movement through the plant.

Assessing water availability for agriculture

The world's agricultural regions include a nearly infinite variety of distinct water resource situations. Precise conditions of microclimate and positioning make each farm unique in terms of water flows. In some cases, variations within an individual farm itself mean that each field may contain multiple zones with different moisture conditions.

The factors most commonly used to classify local hydrological conditions from an agricultural perspective include *potential evapotranspiration* and *mean annual precipitation*. Potential evapotranspiration (commonly abbreviated as PET) is a measure of the hypothetical evaporation and transpiration of a model crop growing in local conditions, and thus encompasses climate factors like temperature, wind speed, relative humidity, and solar radiation. Mean annual precipitation (abbreviated as MAP) is simply the average amount of rain (or snow) received each year. The ratio of mean annual precipitation to total annual potential evapotranspiration (MAP/PET) is used to designate a region's *Climatic Aridity Index*, used to categorize climate conditions for agriculture. The Climatic Aridity Index forms the basis for the characterization of the earth's broad *agroecological zones*, some of which are shown in Table 1.1.

Table 1.1. Agroecological zones of the tropics.[7]

	Agro-ecological zone	Climatic Aridity Index value (MAP/PET)[a]	Characteristics	Native vegetation	Hotspots
	Humid	> 0.65	Growing season > 270 days. Annual rainfall > 1300 mm	Moist forest to rainforest	Equatorial Africa, Caribbean, Pacific Islands, South-east Asia, Amazon basin
	Moist sub-humid	0.50–0.65	Growing season 150–269 days. Annual rainfall 1000–1300 mm	Forest and woodland	Sub-Saharan Africa, Caribbean, South Asia, South-east Asia, Latin America
'Drylands'	Dry sub-humid		Growing season 150–269 days. Annual rainfall 600–1000 mm	Bush, woodland, grassland	
	Semi-arid	0.20–0.50	Growing season 75–149 days. Annual rainfall 250–600 mm	Scrub and bushes, grassland	Sub-Saharan Africa, South Asia, North-east Brazil, Southern China
	Arid	0.05–0.20	Growing season < 75 days. Annual rainfall < 250 mm	Some areas of scrub and grassland	Sub-Saharan Africa, North-east Brazil, Mexico
	Hyper-arid	< 0.05	True desert	Little or none	Saharan Africa, Kalahari Africa, Gobi desert

[a]MAP, mean annual precipitation; PET, potential evapotranspiration.

The dry sub-humid and arid categories on this scale are commonly referred to collectively as *drylands*.[8] Dryland areas cover an estimated 41% of the earth's surface, and these zones are especially vulnerable to both water scarcity and land degradation.[9] The information contained in this book is primarily intended to help farmers working in water-constrained environments across the drylands, though much of the information should also be useful for farmers in moist sub-humid zones that must contend with extended periods without rain. Farms in both humid and dryland areas can lack for water during parts of the growing season; however, extended dry periods are more regular, and tend to have a greater impact, in the latter category. It is also much less likely that unirrigated farms in dryland areas will suffer from excess soil water requiring additional drainage.

Water sources for agriculture

The fundamental source of water in any agricultural system is rain. When rain hits the landscape, it either runs off the surface, eventually contributing to surface water flows, or infiltrates into the soil to be stored as soil moisture or provide groundwater recharge. A distinction can be made here between *blue water*, or water flowing freely in lakes, rivers and groundwater aquifers, and *green water*, or water that is stored as soil moisture and directly available for use by plants. In purely rainfed agriculture, green water stored in the soil is the only source of hydration available to support plant growth. In irrigated agriculture, blue water reserves are drawn upon through a variety of methods in order to provide additional water beyond what the soil would otherwise provide. Agricultural projects will lie somewhere on the continuum of green to blue water use – that is, from complete reliance on rainwater to full dependence on irrigation. Figure 1.3 outlines the range of water source situations in agriculture.[10]

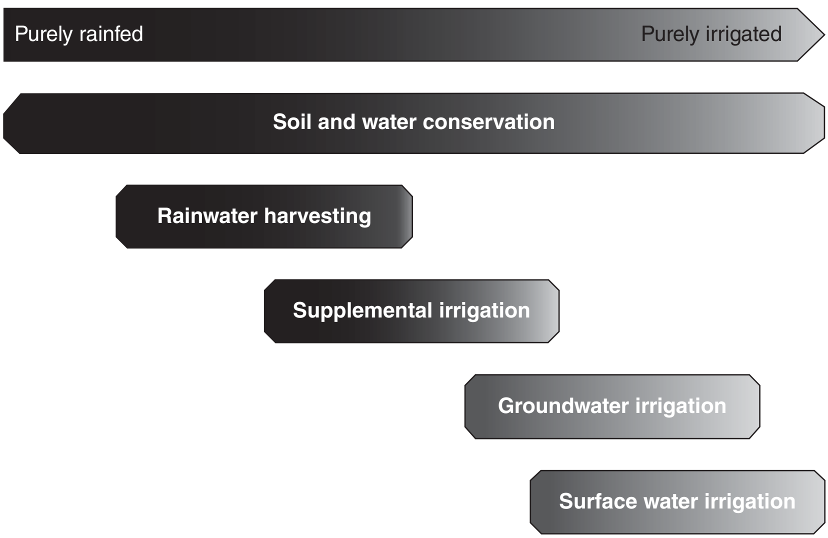

Fig. 1.3. Continuum of practices in agricultural water management.

Irrigation

Irrigation is the process of moving water from a reservoir, a groundwater well, or a surface water body and applying it to the field using some form of distribution mechanism. The advantage of irrigating crops is that the farmer can control the timing and volume of water applications in order to maintain a favorable soil moisture environment for plant growth. Irrigation equipment also allows for the expansion of land area under cultivation. In most cases and under the right conditions, irrigation can increase crop production yield by 100–400%.[11] Irrigation development can also improve farming livelihoods by providing a buffer against periods of drought and allowing for the production of high-value crops that may demand more water than rainfall patterns can naturally provide.

Nearly 80% of the world's cropland is exclusively rainfed, with no formal irrigation equipment.[12] However, the total area of irrigated land worldwide has increased drastically in the past half-century as a result of modern farming technology and industrial agriculture: between 1961 and 2001 alone, the area of land under irrigation worldwide nearly doubled.[13] Most of the world's irrigated farmland is located in the USA and Asia, but irrigation expansion has been actively promoted over the last few decades throughout South America, South Asia, and the Middle East as part of a global effort to improve agricultural yields.[14]

The yield improvement potential of irrigation is impressive. However, it is important to understand that some forms of irrigation carry the risk of detrimental long-term effects on soil and water sources that can lead to a decrease in productivity over the long run. Irrigation choices must be very carefully considered with an eye on the potential for negative environmental consequences.

There are many different methods of irrigation, ranging in complexity from simple methods of hand-watering and flood irrigation to highly mechanized systems of pumps, pipes, and sprinklers. Common forms of irrigation are covered in Chapter 10.

Water Management Planning

Some degree of *farm water management planning* is recommended for any farmer working in a water-constrained environment. Water management planning involves estimating how much water crop plants require, taking stock of the amount of water they are supplied, and outlining possible strategies for overcoming shortfalls between the two. Because farming practice involves a considerable amount of trial and error, the financial cost and expected yield benefit of proposed investments in new practices or infrastructure should be considered in the context of an integrated farm water management plan before being implemented.

Decisions about farm water management should:

- take into account site-specific information about rains, soils and climate as well as their evolution over time;
- seek to sustain the availability of local water resources over the long term;

- seek to nourish the health of the natural environment on and around the farm; and
- consider the potential risks associated with changing practices.

The high degree of risk inherent to smallholder agriculture makes it difficult to plan for future investments, but farm water management planning can be an easy first step. The initial stages of the plan should be designed to reduce the overall risk of crop failure during dry periods through the implementation of incremental and low-cost improvements. This can secure the path forward for subsequent water productivity investments.

Key concepts in water management planning

The following concepts are useful in understanding and quantifying water management objectives: (i) water productivity; (ii) water use efficiency (WUE); and (iii) efficiency of investments in water productivity.

Water productivity

Water productivity is an expression of the amount of product (crop yield or financial benefit) produced per unit of water (cm or m^3) applied to the field as rain or irrigation. Improving water productivity is commonly referred to as producing '*more crop per drop*' of water used.[15]

Upgrading farm water infrastructure or implementing new water management strategies can require significant investment. Monitoring water productivity values before and after new strategies are implemented provides a sense of the return on investment yielded by each new upgrade.

Equation 1.1

$$\text{Water productivity} = \frac{\text{Crop yield}\left(\begin{matrix}\text{wet or dry crop yield in kg,}\\ \text{or economic return in \$}\end{matrix}\right)}{\begin{matrix}\text{Total water applied as rain and/or}\\ \text{irrigation}\left(\text{in cm or } m^3\right)\end{matrix}}$$

Water productivity (commonly expressed as kg/m^3 or \$/m^3) is used as basis for goal-setting when developing an integrated water management plan for agricultural projects. In rainfed agriculture, the term *rainwater productivity* is often used.

Water use efficiency (WUE)

WUE is a term that has a range of definitions, and is sometimes used interchangeably with water productivity. In general, WUE is used to express the overall efficiency of water delivery on farms where irrigation is practiced. WUE terms are normally a variation of the basic efficiency formula of OUTPUT/INPUT. *Irrigation efficiency* (IE) is used to evaluate the efficiency of irrigation network design, and is often broken down into components of storage, conveyance, and application efficiencies. These values provide useful information about the health of irrigation equipment and provide targets for infrastructure improvement.

In this book, where the focus is improving water productivity on primarily rainfed smallholdings, efficiency terms are used to evaluate the increase in yield that is achieved by each new investment in water management practices. In this context, water use efficiency, $WUE_{(IRR)}$ is a measure of the increase in crop yield that is achieved per unit of water added as irrigation, as compared to the average crop yield achieved without irrigation (unimproved yield).[16] This provides an estimate of the productivity benefit of each drop of irrigation water added to a primarily rainfed farm, and it can be used to assess the yield impact of water used in irrigation:

Equation 1.2[17]

$$WUE_{(IRR)} = \frac{Yield\ (improved,\ in\ kg\ or\ \$) - Yield\ (unimproved,\ in\ kg\ or\ \$)}{(Additional)\ water\ volume\ applied\ as\ irrigation\ \left(in\ cm\ or\ m^3\right)}$$

Efficiency of investments in water productivity

Of course, it is also useful to estimate the yield impact of investments other than irrigation. The water management practices outlined in this book include not only irrigation development, but also soil improvements, cropping practices, and land-shaping work designed to improve the water productivity of rainfed farms. These investments can also be viewed with an eye to efficiency:

Equation 1.3

$$Investment\ efficiency = \frac{Water\ productivity\ \left(improved,\ in\ kg\ or\ \$/m^3\right) - Water\ productivity\ \left(unimproved,\ in\ kg\ or\ \$/m^3\right)}{Investment\ made\ in\ new\ practices\ (hours\ and\ \$)}$$

This equation provides a simple and useful means to evaluate the water productivity benefit derived from each new practice adopted. It yields the equivalent of what is commonly called the *cost-benefit ratio* of the investment (though mathematically it is actually a benefit-cost ratio). Measurable yield improvements are achievable through the adoption of improved water management practices on rainfed farms. However, not all upgrades are ‘affordable’, so investment efficiency is an important consideration in water management planning.

References

1 United States Geological Survey (USGS). Where is Earth’s water? USGS Water-Science School. *water. usgs.gov*. Available at: http://water.usgs.gov/edu/earthwherewater.html [Accessed November 4, 2015].

[2] Intergovernmental Panel on Climate Change (IPCC), 2015. *IPCC Fifth Assessment Report (Ar5) 2014*. Geneva, Switzerland: IPPC, p. v.

[3] IPCC, 2014. Climate Change, 2014. Synthesis Report. *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri & L.A. Meyer (eds)]. Geneva, Switzerland: IPCC, 151 pp.

[4] IPCC, 2007. 9.4.4 Agriculture – AR4 WGII Chapter 9: Africa. *ipcc.ch*. Available at: https://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch9s9-4-4.html [Accessed November 5, 2015]. Based on data from: Agoumi, A., 2003. Vulnerability of North African countries to climatic changes: adaptation and implementation strategies for climatic change. *Developing Perspectives on Climate Change: Issues and Analysis from Developing Countries and Countries with Economies in Transition. IISD/Climate Change Knowledge Network*, *14*.

[5] Postel, S.L., 2003. Securing water for people, crops, and ecosystems: new mindset and new priorities. *Natural Resources Forum*, 27(2), pp. 89–98.

[6] Steduto, P. *et al*., 2012. *Crop Yield Response to Water*. Rome: Food and Agriculture Organization of the United Nations (FAO).

[7] Table compiled from data from: (i) Rockström, J. *et al*., 2007. Managing water in rainfed agriculture, in *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. London: Earthscan; and (ii) United Nations Environment Programme (UNEP), Millennium Ecosystem Report, Chapter 22 Drylands. *unep.org*. Available at: http://www.unep.org/maweb/documents/document.291.aspx.pdf [Accessed August 16, 2015]. Note that the second reference does not qualify Hyper-arid climate zones as part of the 'dryland' category.

[8] Millennium Ecosystem Assessment, 2005. Drylands systems, Chapter 22, in *Ecosystems and Human Wellbeing: Current State and Trends*, Volume 1. Washington, DC: Island Press. Note that not all classification schemes include Hyper-arid climate zones in the 'dryland' category.

[9] Ibid. p. 625.

[10] Comprehensive Assessment of Water Management in Agriculture, 2007. *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. London: Earthscan, and Colombo: International Water Management Institute, p. 11.

[11] FAO Land and Water Development Division, 2003. *Unlocking the Water Potential of Agriculture*. Rome: FAO, p. 1.

[12] Rockström, J. *et al*., 2007. Managing water in rainfed agriculture, in *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. London: Earthscan and Colombo: IWMI, p. 1.

[13] Farurès, J.-M. *et al*., 2007. Reinventing irrigation, in *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. London: Earthscan and Colombo: IWMI, p. 356.

[14] Ali, M.H., 2010. Fundamentals of irrigation development and planning, in *Fundamentals of Irrigation and On-farm Water Management,* Volume 1. New York: Springer, p. 20.

[15] Tow, P. *et al*., 2011. Principles of a systems approach to agriculture, in P. Tow *et al.,* eds, *Rainfed Farming Systems.* Dordrecht, The Netherlands: Springer, p. 33.

[16] Adapted from: (i) Howell, T.A., 2001. Enhancing water use efficiency in irrigated agriculture. *Agronomy Journal*, 93(2), pp. 281–289; (ii) Oweis, T. (1997) *Supplemental Irrigation*. Aleppo, Syria: International Center for Agricultural Research in the Dry Area (ICARDA); and (iii) Oweis, T. & Hachum, A. (2012) *Supplemental Irrigation: A Highly Efficient Water-use Practice*, 2nd edn. Aleppo, Syria: ICARDA.

[17] Ibid.

2 Goals of Agricultural Water Management

Water is a vital component of every agricultural project. In addition to supporting plant growth, water is critical to maintaining soil health and promoting the overall ecological well-being of the land, which are essential in ensuring the long-term viability of the farm. In this book, the term *soil and water management practices* is used to designate the range of farming practices that influence the way in which water flows through the farm environment and is transformed into crop yields. This category includes methods of water application, but also cropping systems, soil management practices, and land use patterns. The purpose of this publication is to define and explain sound practices for managing water in the cultivation of field crops. While the management of soil and water resources is equally important in other agricultural categories such as livestock rearing, aquaculture and forestry, these remain outside of the scope of this book.

Ultimately, the goals of soil and water management practices are threefold:

1. They serve to reduce the farm's vulnerability to variations in water availability.
2. They help to produce higher yields within a limited water budget.
3. They are key to preventing land degradation, which can destroy the health and productivity of the farm.

Goal #1: Reducing Vulnerability

Farming, especially rainfed farming, is an inherently risky activity. The success of seasonal harvests is heavily dependent on a variety of climate factors that are beyond the farmer's control. When it comes to water supply, the principal source of vulnerability in rainfed farming is the high variability of rainfall patterns. Rainfall (and overall precipitation) values can be highly unpredictable in terms of both timing and amount, and they commonly fluctuate wildly from one year to the next. Seasonal precipitation values are doubly crucial in agriculture because they not only affect the reserves of green water that will be stored in farm soils, but also determine the relative quantity of blue water that will be available in wells, lakes and rivers for use in irrigation.

Precipitation is highly variable in terms of: (i) amount (mm/year); (ii) timing (seasonality); (iii) distribution within rainy season(s); and (iv) intensity and duration.

Precipitation amount (mm/year)

The *mean annual precipitation (MAP)* provides an overall average of annual precipitation values recorded over a long period of time (usually more than 30 years) in a given region. However, it does not provide information about the year-to-year variation in precipitation within that period. In many regions, a wide divergence between MAP values and actual annual precipitation depth makes it difficult to predict seasonal rainfall with any accuracy. In the Sahel region, for example, annual rainfall values can vary by up to 40% from one year to the next.[1]

Precipitation timing (seasonality)

In most of the world, the majority of annual rainfall occurs during a few months of the year, collectively known as the *rainy season* or *wet season*. Some areas have two rainy seasons per year (bimodal rainfall pattern) while others have only one (unimodal rainfall pattern). Traditionally, the growing season for cultivated crops is planned according to the timing of the local rainy season(s). When field preparation tasks and planting dates are scheduled in relation to the onset of the rainy season, any variability in the date of first rains can jeopardize the success of the crop. Similarly, if the last rains of the season come early or late, the final harvest can be affected.

Precipitation distribution within rainy season(s)

The occurrence of rain events within the wet season itself can be highly irregular, causing wide fluctuations in soil moisture availability. Short periods without rain that occur during the wet season are known as *dry spells*: these typically last a few days to a few weeks and can cause substantial crop stress if soil moisture drops below a critical point. Dry spells that occur during critical stages of crop development can have a significant and irreversible impact on yields.

Longer periods without rain are called *droughts*. Droughts can last from several weeks to several years, during which time crops are subjected to severe water stress and eventually fail. Drought can occur anywhere, but is more common in semi-arid and arid zones, where annual rainfall values are low and variability is high.

Contrary to popular belief, the droughts experienced by farmers are not usually meteorological in origin: most are in fact caused by bad timing, compounded by farming practices that fail to reinforce the soil's ability to effectively capture and store rainfall.[2] These so-called '*agricultural droughts*' occur not because the absolute volume of rainfall is insufficient, but because farm soils are unable to store enough moisture to mitigate water-stress-induced crop damage during extended dry spells within the growing season.[3]

Precipitation intensity and duration

The intensity and duration of individual rain events is very influential in determining the proportion of rainfall received that will become *effective rainfall*, that is, water stored in the soil and accessible to plants.[4] Tropical areas frequently experience heavy storms and rapid bursts of high-intensity rainfall. These powerful, brief rain events are very difficult to manage in farming: soil does not have adequate time to absorb the high volume of falling water, and the excess will tend to pool up and run off of the soil surface. Long, low-intensity rainfall is most effective in promoting water infiltration and storage in the soil. Unfortunately, these types of rain events are not the norm, and rainfall intensity is only expected to increase in the years to come due to the effects of global climate change.[5]

Heavy rains are a leading cause of erosion, waterlogging, and nutrient leaching.[6] Flash flooding during storms can also damage crops and contribute to the proliferation of pests and disease. The absence of indigenous and deep-rooted vegetation on farm fields leaves exposed soils vulnerable to degradation by strong rains – this is especially true in dryland areas, where infrequent and intense rains can be more damaging than beneficial for loose, dry agricultural soils.[7]

The first goal of soil and water management practices is to **reduce the farm system's vulnerability to variations in rainfall amount, timing, distribution, and intensity**. This is done by encouraging *resilience*, that is, the capacity of crops and soil to withstand occasional dry spells and bounce back after periods of stress. In dry sub-humid and semi-arid climates, crop yields have been found to be limited more by the occurrence and timing of dry spells during the growing season than by total annual rainfall amounts.[8] Reducing farms' vulnerability to crop damage during dry spells is therefore crucial to providing good yields within the reality of highly variable rainfall. This goal is especially pertinent on purely rainfed farms that depend on unpredictable precipitation patterns, but promoting resilience is also very important on farms where irrigation is practiced. Resilience is intricately linked to the ecological health of the farm and its soils.

Goal #2: Producing Higher Yields from Within a Limited Water Budget

In rainfed farming, the farmer has little control over the absolute quantity of water that will be delivered to the field each season. Even when some form of irrigation is in place, the effort required to move water from place to place, coupled with the scarcity of the resource, should motivate farmers to use each drop wisely. Before seeking to increase the amount of water applied to the field, it is important to ensure that the crop is able to efficiently access and use the water that is stored in the soil. This is commonly referred to as producing 'more crop per drop'. New water inputs and/or investments in irrigation equipment should only be investigated once efficiency is maximized within the existing water budget.

Let's imagine the plant–soil environment as a closed system, where all water INPUTS are transformed into a corresponding amount of water USES. This is similar to a household spending budget, where a fixed income is used to purchase a corresponding quantity of goods and services. Like in a household budget, water inputs must be 'spent' wisely so that maximum benefits can be derived from a limited supply. Water stored in the soil is being 'saved' for future use.

Fig. 2.1 presents a conceptual representation of the farm water budget.

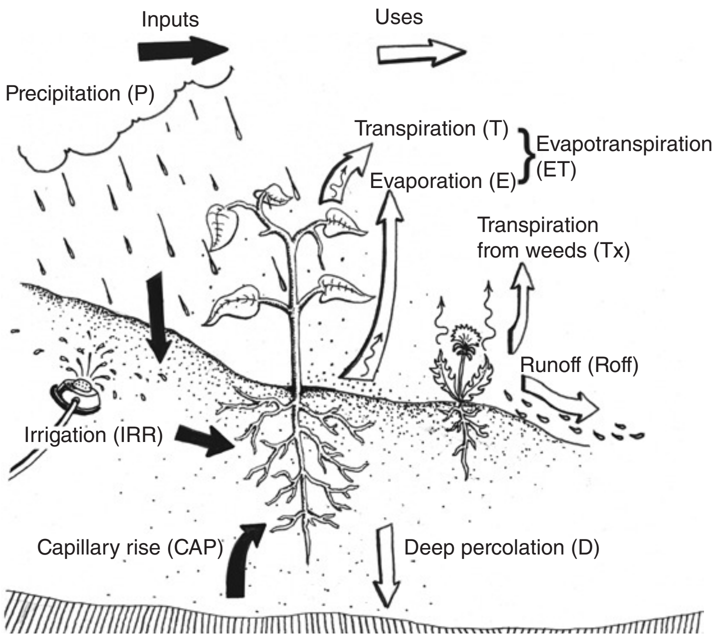

Fig. 2.1. Water inputs (dark arrows) and uses (light arrows) in crop production.[9]

Water INPUTS (dark arrows in Fig. 2.1) include rainfall/precipitation – (P) and, in irrigated projects, blue water applied as irrigation (IRR). In areas with shallow aquifers, there will also be some input from the capillary rise of groundwater into the root zone (CAP) (Fig.2.2).

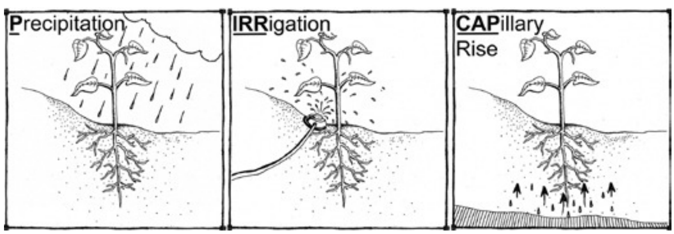

Fig. 2.2. Water inputs.

Water USES (light arrows in Fig. 2.1) include crop transpiration (T), evaporation (E), water runoff (Roff), water taken up by weeds (Tx), and deep percolation (D) (Fig. 2.3).

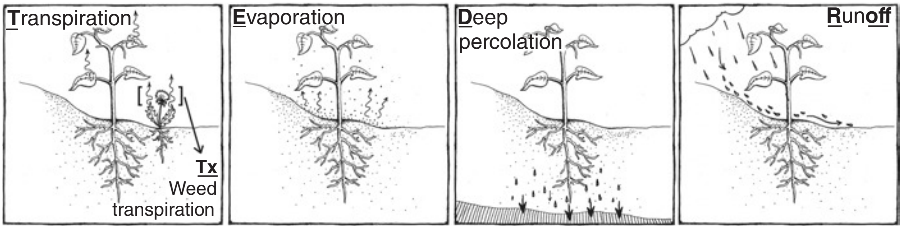

Fig. 2.3. Water uses.

Of these water uses, only the first one on the list, transpiration (T), is considered to be a *productive* use of water: this is the portion that will ultimately be transpired by crop plants and therefore contributes directly to crop yields. The remaining water uses: evaporation, deep percolation, weed growth and runoff, are largely unproductive and can be treated as water 'losses' from the system.

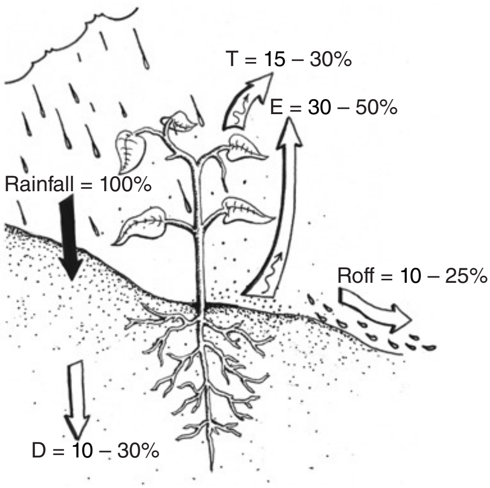

Fig. 2.4. Partitioning of water flows.[10]

On most rainfed farms, less than 30% of the total rainwater inputted into the farm system is ultimately channeled toward crop transpiration (Fig. 2.4).[11] This means that more than 70% is lost to some combination of evaporation, runoff, deep percolation and weeds. This proportion varies by region: in sub-Saharan Africa, it is estimated that between 15% and 30% of rainwater is ultimately productive, but on severely degraded land the value can be as low as 5%.[12,13] These are indeed discouraging statistics, but they also leave much room for improvement, suggesting that there exists significant potential to increase yields through the adoption of soil and water management practices that improve rainwater partitioning.

The second goal of water management in agriculture is therefore to **improve the crop yield produced within the existing and available supply of water**. This means minimizing water losses in order to increase the proportion of water inputs available for productive use by the plant. This allows farmers to improve yields within existing water supplies, which is generally more economical and labor-efficient than investing in new water inputs or installing irrigation equipment.

Goal #3: Preventing Land Degradation

Land degradation is the gradual destruction of soil quality to the point where it becomes impossible to bring it back to productive health without significant outside assistance.[14] Degraded land is no longer able to support crops or provide ecosystem services for people and the wider environment.

Widespread land degradation is a serious threat to food production systems worldwide.[15] The Food and Agriculture Organization of the United Nations (FAO) estimates that severe land degradation has already decimated 25% of the world's productive farmland, and the trend does not show signs of slowing.[16] In sub-Saharan Africa, it is estimated that a full 65% of agricultural land is affected by some form of degradation, and in Central America 75% of cropland is already seriously degraded.[17,18] Globally, the combined effects of various forms of land degradation are causing productivity to decline on over 40% of the land area devoted to rainfed farming.[19]

Land degradation is linked to climate variations, but its principal cause is unsustainable land use by humans. Most forms of degradation are directly associated with the removal of native vegetation to make room for human activities, among which agriculture and livestock rearing are the leading culprits. Sadly, many modern farming practices fail to promote the natural cycling of water and nutrients that sustains soil health. Across the globe, unsustainable agricultural practices are allowing once-rich lands to become depleted to the point where they are no longer able to sustain crops or even native vegetation.

Water plays a pivotal role in land degradation processes. One of the major impacts of degradation is a loss of water retention capacity, and the process tends to be self-reinforcing: dry soil is more vulnerable to degradation, and degraded land is less able to capture and retain rainwater.

The principal effects that contribute to land degradation are described below. These processes tend to be closely related and often occur simultaneously.

Soil erosion by wind or water

Erosion occurs when soil particles are swept away by the forces of wind or water. In undisturbed natural landscapes, native vegetation protects the soil from erosion by binding it around a network of thick, dense roots. When land is cleared for farming, this protection is removed. Tilling further loosens the soil profile, leaving it exposed to erosion. Soil erosion is most problematic in areas subjected to deforestation, agricultural development, or overgrazing by livestock. Erosion not only damages the soil profile, it also causes water pollution by increasing the sediment concentrations of downstream water bodies.[20]

Water-driven erosion of farmland is primarily caused by rainfall and the run-off it generates: water flowing off the land surface during rain events will pick up soil particles in its path and deposit them at the bottom of the slope or into nearby water bodies. Heavy rains and floods are highly erosive and cause significant losses of topsoil with each event. Because the process is exacerbated when strong rain strikes bare earth, dryland agricultural areas that experience occasional bursts of intense rainfall are especially vulnerable to this type of erosion.[21]

Wind-driven erosion occurs when strong winds pick up and transport soil particles from place to place. Dry, bare soils in areas with poor tree cover are especially vulnerable. Wind erosion causes significant soil loss in arid and semi-arid plains where wind speeds are high during the dry season.[22]

Desertification

Desertification is a worrisome trend that threatens the vitality of dryland areas across the globe. As the name would suggest, desertification is the transformation of once fertile land into desert. It is most often caused by a combination of land clearing, drought, and the deterioration of soil health through intensive farming or overgrazing by livestock.[23] Desertification is an irreversible process that destroys millions of hectares of farmland every year, affecting over 1 billion people worldwide.[24] Sub-humid, semi-arid and arid landscapes are all vulnerable to desertification, but it is especially rampant on arid lands on the fringes of true deserts.[25]

Chemical degradation

Significant chemical changes can occur in the soil when native vegetation is cleared to make room for agriculture. The plant growth and decomposition cycles that provide chemical balance in virgin soils are interrupted in most forms of agricultural production because plant residues are routinely removed instead of decomposing in place. This causes the gradual depletion of vital nutrients and leads to a harmful buildup of trace elements that can be toxic to plants, coupled with a shortage of other elements that they require.[26] What's worse, weeds may continue to thrive in chemically unbalanced soil, consuming precious soil water and nutrients as they grow. Chemical contamination of soil is especially pronounced in the humid and sub-humid tropics.[27] Soil acidification, wherein continuous cropping and the application of ammonia-rich fertilizers causes a lowering of soil pH, is problematic in both humid and dryland areas.[28]

Salinization

Soil *salinization* is the accumulation of free salts in the soil to levels where it becomes excessively difficult for plants to extract soil water. Salinization is most often associated with irrigated agriculture, and the FAO estimates that a full 20% of the world's irrigated land now suffers from some degree of excess salinity.[29]

Salinization is caused by rising groundwater tables, a condition brought about by a combination of human and environmental factors. As groundwater moves up through the soil subsurface, salts naturally present in subsoil layers become mobilized and dissolve into the water, leading to the formation of shallow, saline aquifers.

The main cause of rising water tables is the clearing of deep-rooted native vegetation for replacement by shallow-rooted agricultural crops that use and reach less water. In irrigated agriculture, the process is further intensified by repeated water applications that cause an imbalance between drainage and water added. Groundwater pumping also accelerates salt accumulation. When water from a shallow saline aquifer is used to supply irrigation, the result is a vicious circle of salt buildup in the topsoil leading to a loss of productivity.[30]

Soil salinity is a major source of land degradation worldwide, causing serious loss of agricultural productivity especially in arid and semi-arid areas, where rainfall is insufficient to flush excess salts from the soil. Farms that practice full irrigation in very dry climates are always affected by some degree of salinization.[31]

Soil *sodicity* is a related problem wherein the sodium accumulation in saline soils reaches such an extent that it modifies the structure and infiltration capacity of the soil. Sodic soils have very poor drainage and are prone to waterlogging. Like salinity, sodicity is most common on irrigated farms in arid and semi-arid zones.[32]

Soil degradation

Physical soil degradation (deterioration of soil structure) and biological soil degradation (loss of nutrients, organic matter, and water holding capacity) are of concern in most agricultural projects, spanning all climate zones. Land used for agriculture is especially susceptible to soil degradation because most conventional agricultural practices fail to regenerate the soil following the crop growing period, causing it to slowly diminish in health year after year. This results in continually decreasing nutrient levels and a loss of organic matter. Organic matter depletion leads to surface compaction and crusting, which make it harder for the soil to absorb the water it needs to sustain a healthy subsoil ecosystem. This in turn causes it to dry and deteriorate ever more in a vicious cycle of escalating degradation. If this trend continues unchecked, agricultural soils will no longer be able to sustain crops after only a few years of continuous cultivation and must eventually be abandoned.

Because water is so critical to soil health, soil management and water management are, in practice, indistinguishable; both are key aspects of an integrated approach to maintaining the health of the land. Land degradation and drought are intimately linked, and these two factors compounded together can lead to spiraling decreases in both soil fertility and crop yield. The **maintenance of soil health to discourage land degradation** is thus the third goal of agricultural water management. Effective management of water and soil resources is critically important in agriculture, both to provide crop yields and to preserve the vitality of agricultural lands for future generations.

Further reading – Land degradation

Climate and Land Degradation, by the World Meteorologial Organization. Available at: http://www.droughtmanagement.info/literature/WMO_climate_land_degradation_2005.pdf

The State of the World's Land and Water Resources for Food and Agriculture (SOLAW) – Managing Systems at Risk, report from the Food and Agriculture Organization of the United Nations (FAO). Available at: http://www.fao.org/docrep/015/i1688e/i1688e00.pdf

Meeting the Goals

The three goals outlined in this chapter can be addressed in overlapping ways through improved soil and water management practices. The various practices outlined in this book seek above all to:

1. Reduce vulnerability while promoting resilience.
2. Minimize unproductive water uses (water losses).
3. Promote the long-term health of the soil.

Though the objectives presented here may seem broad, all three can be addressed through the gradual adoption of an interrelated set of strategies at the single-farm level, and real and measurable improvements are often achievable without a high degree of financial investment.

References

[1] Food and Agriculture Organization of the United Nations (FAO), Land and environmental degradation and desertification in Africa. *fao.org*. Available at: http://www.fao.org/docrep/X5318E/x5318e02.htm#The%20magnitude%20of%20the%20problem [Accessed December 5, 2012].

[2] Rockström, J., 2003. Resilience building and water demand management for drought mitigation. *Physics and Chemistry of the Earth*, 28(20–27), pp. 869–877.

[3] Ibid. p. 872.

[4] Brouwer, C. & Heibloem, M., 1986. *Irrigation Water Management: Irrigation Water Needs*. Training Manual. Rome: FAO. Available at: ftp://193.43.36.92/agl/AGLW/fwm/Manual3.pdf [Accessed February 15, 2015].

[5] Intergovernmental Panel on Climate Change (IPCC), 2015. *IPCC Fifth Assessment Report (Ar5) 2014*. Geneva: IPPC, p. 53.

[6] Koohafkan, P. & Stewart, B.A., 2008. *Water and Cereals in Drylands*. London: Earthscan and Colombo: IWMI, p. 43.

[7] World Meteorologial Organization (WMO), 2005. *Climate and Land Degradation*. Geneva, Switzerland: WMO. *wmo.int*. Available at: http://www.droughtmanagement.info/literature/WMO_climate_land_degradation_2005.pdf [Accessed June 10, 2016].

[8] Barron, J. *et al.*, 2003. Dry spell analysis and maize yields for two semi-arid locations in East Africa. *Agricultural and Forest Meteorology*, 117(1–2), pp. 23–37.

[9] Adapted with permission from Rockström, J., 2003. Resilience building and water demand management for drought mitigation. *Physics and Chemistry of the Earth*, 28(20–27), pp. 869–877.

[10] Adapted with permission from Rockström, J. *et al*., 2003. Water productivity in rain-fed agriculture: challenges and opportunities for smallholder farmers in drought-prone tropical agroecosystems, in *Water Productivity in Agriculture*. Wallingford, UK: CABI, p. 151.

[11] Ibid. p. 150.

[12] Ibid.

[13] Wani, S.P. *et al*., 2009. *Rainfed Agriculture: Unlocking the Potential*. Wallingford, UK: CABI, p. 19.

[14] International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), 2008. Agriculture at a Crossroads: Sub-Saharan Africa (SSA) Report, B. McIntyre *et al*., eds. Washington, DC: Island Press, p. 4.

[15] FAO, 2011. *The State of the World's Land and Water Resources for Food and Agriculture (SOLAW) – Managing Systems at Risk*. London: Earthscan and Colombo: IWMI, p. 113.

[16] Ibid. p. 113.

[17] IAASTD, 2012. Agriculture at a Crossroads: Volume V Sub-Saharan Africa. Subglobal Report. Washington, DC: Island Press, p. 62.

[18] Koohafkan, P. & Stewart, B.A., 2008. *Water and Cereals in Drylands*. London: Earthscan and Colombo: IWMI, p. 21.

[19] Hansen, S. & Bhatia, R., 2004. *Water and Poverty in a Macro-economic Context*. Oslo: Norwegian Ministry of the Environment, p. 13.

[20] Koohafkan, P. & Stewart, B.A., 2008. *Water and Cereals in Drylands*. London: Earthscan and Colombo: IWMI, pp. 22–23.

[21] WMO, 2005, *Climate and Land Degradation*. Geneva, Switzerland: WMO. *wmo.int*. Available at: http://www.droughtmanagement.info/literature/WMO_climate_land_degradation_2005.pdf [Accessed 10 June 2016]. p. 14.

[22] Ibid. p. 22.

[23] Eswaran, H., *et al*., 2001. Land degradation: an overview, in E.M. Bridges *et al*., eds, *Responses to Land Degradation*, Proceedings of the 2nd International Conference on Land Degradation and Desertification, Khon Kaen, Thailand. New Delhi, India: Oxford University Press, pp. 20–35.

[24] Ibid.

[25] WMO, 2005, *Climate and Land Degradation*. Geneva, Switzerland: WMO. *wmo.int*. Available at: http://www.droughtmanagement.info/literature/WMO_climate_land_degradation_2005.pdf [Accessed 10 June 2016]. p. 12.

[26] Kuile, C., The humid and subhumid tropics. *ifpri.org*. Available at: http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/129414 [Accessed June 10 2016]. p. 103.

[27] Ibid.

[28] International Fund for Agricultural Development (IFAD) & United Nations Environment Programme (UNEP), 2013. *Smallholders, Food Security and the Environment*. Rome: IFAD, p. 24.

[29] Koohafkan, P. & Stewart, B.A., 2008. *Water and Cereals in Drylands*. London: Earthscan and Colombo: IWMI, p. 22, quoting Ghassami, F., Jakeman, A.J. & Nix, H.A., (1995) *Global Salinization of Land and Water Resources: Human Causes, Extent and Management*. Canberra: Centre for Resource and Environmental Studies, Australian National University, pp. 211–220.

[30] Tanji, K.K. & Kielen, N.C., 2002. Agricultural drainage water management in arid and semi-arid areas. *FAO Irrigation and Drainage Papers*, 61, p. 3.

[31] Ali, M.H., 2011. Management of salt-affected soils, in *Practices of Irrigation & On-farm Water Management*, Volume 2. New York: Springer, p. 275.

[32] Ibid. p. 272.

3 Soil and Water

More than anything else, the key to enhancing resilience and promoting water availability for crop growth lies in the proper care of farm soils. In fertile regions, the native soil underlying forests, brush or grasslands tends to be naturally 'healthy', that is, rich in nutrients with good structure and organic matter content. When land is cleared for farming, soil can quickly lose its 'healthy' qualities, especially if farming practices employed do not encourage its regeneration. Without proper management, agricultural soils can become completely depleted in as little as a few decades or even a few years after clearing, depending on the nature of the land and its use.[1]

Some negative effects that agriculture can have on the soil include:

- nutrient mining (continual removal of nutrients without renewal);
- breakdown of organic matter;
- loss of water holding capacity;
- compaction;
- erosion;
- surface sealing (crusting); and
- deterioration of natural habitat for soil organisms (microorganisms, insects, and worms).

Growing crops in depleted soil requires much more water, more chemicals and more effort than it does in healthy soil. Yields will tend to be lower and crop plants will lack resilience, leaving them more vulnerable to drought, pests and disease.[2]

Declining soil quality often prompts farmers to increase the application of chemical fertilizers and pesticides as a compensation measure. While these inputs have short-term productivity benefits, they do little to improve the health of the soil, and their use can create a dependency that requires the purchase of costly inputs with each new season.[3] Sustainable soil management, sometimes known as *soil conservation*, involves creating the right conditions for the natural regeneration mechanisms that provide soil structure, build organic matter, and maintain fertility in a natural system. This approach reduces the labor and inputs required to keep the soil productive over time.

Growing crops while maintaining natural soil functions presents a special challenge, since crop production requires the continuous extraction of water, nutrients and other elements from the soil to produce food. In traditional agriculture, long periods of fallow were used to regenerate soils depleted by repeated cultivation. In the absence of long fallow periods, *sustainable land management* is imperative to keep agricultural soils healthy and prevent land degradation.

Understanding Healthy Soil

Healthy soil is often referenced as the key to good crop yields and long-term sustainability. But what makes soil healthy? Table 3.1 describes some differences between healthy and unhealthy (depleted) soil, and Fig. 3.1 shows how plants can be indicators of soil health.

Table 3.1. Healthy versus depleted soil.[4]

Characteristic	Healthy soil	Depleted soil
Texture	Soft with different sizes of particles, lumps, and clumps	Hard and dry, cracks and crumbles easily
Depth	Workable soil extends deep (> 50 cm) into the ground	Workable soil is shallow or a hardpan (rigid layer of unworkable soil) is present (< 50 cm)
Soil life	Many worms and insects	Few or no worms, little soil life can be observed
Runoff	Rain is absorbed easily and rapidly	Soil ridges form from rain runoff, rain is absorbed slowly or water pools and runs off
Organic matter	Soil is dark and rich with plant residues	Soil is light-colored and seems to contain nothing else
Water holding capacity	Soil stays moist for days between rains	Soil dries out rapidly after rain
Yields	Yields stay stable or get better from year to year	Yields decrease from year to year
Root growth	Roots are healthy and strong, taproots grow straight down into the soil	Roots are generally spindly and weak, taproots grow sideways instead of straight down
Crop health and resilience	Crops seem vigorous and are resistant to variations in climate	Crops are weak and yellowed, and suffer from slight variations in climate

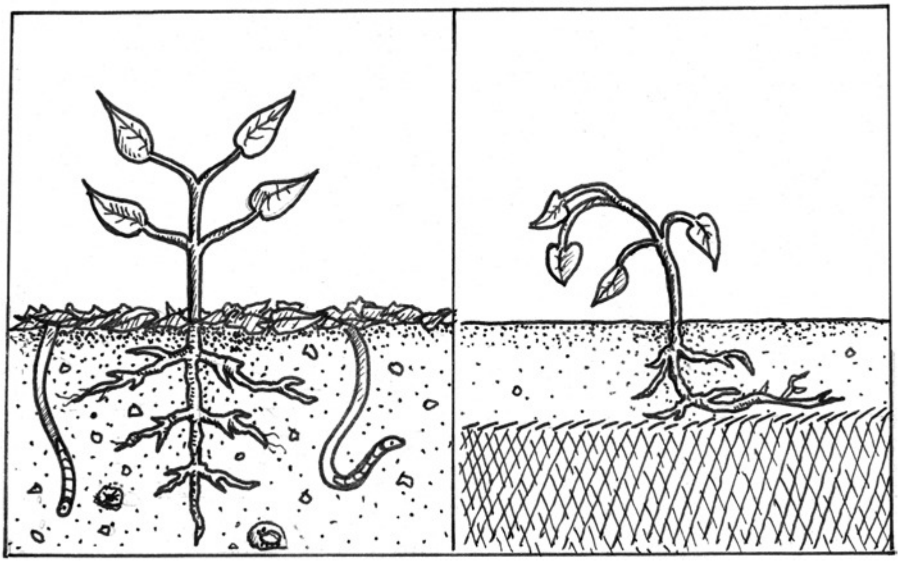

Fig. 3.1. Plants in healthy soil (left) and depleted soil (right).[5]

Water movement through soil and plants

Soil is the plant's water delivery mechanism. Water arriving via rain or irrigation is first stored in the tiny pores between soil particles, then is gradually absorbed by plant roots according to the relative dryness and extraction capacity of the plant. From there, it slowly migrates upward through plant stems, tissues and leaves before finally exiting into the atmosphere as transpiration through tiny pores on the leaf surface.

The upward movement of water through the soil to the plant is driven by solar energy. When the sun is shining, plant transpiration accelerates, causing an upward water potential gradient, essentially a 'suction' of water toward the leaves from within the plant. The plant then absorbs more soil water through its roots in order to replace that which was lost through transpiration. The *soil–plant–atmosphere continuum* thus works as an unbroken chain of water movement, channeling water from soil moisture through plant tissues and out into the air in a continuous sequence (Fig. 3.2).[6]

Of the water taken up by the plant, only roughly 1% will be consumed as fuel for the plant's functions, including photosynthesis and the creation of biomass. The remaining 99% is ultimately transpired into the atmosphere unchanged.[7] This water is nonetheless useful for plant functions because it provides structure and facilitates the movement of sugars and essential nutrients through plant tissues.

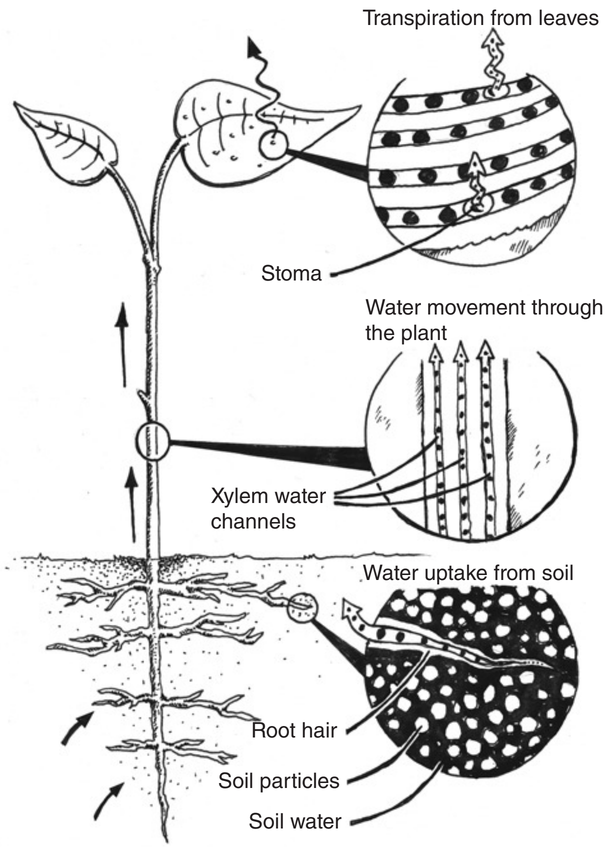

Fig. 3.2. Water movement through the soil–plant–atmosphere continuum.

Soil infiltration

Water arriving at the soil surface is absorbed into the soil profile through a process known as *infiltration*. The dynamics of water infiltration through the first layers of soil are especially dependent on the size and distribution of soil pores, which are themselves a function of soil type. (See Box 3.1 for more information about soil type.) Coarse-textured soils (including sand and sandy loam mixtures) will infiltrate water quickly, but the heavy droplets of water contained in their large pores tend to pass quickly downward and out of the root zone. Fine-textured soils, like those with high clay content, infiltrate water much more slowly, but the small droplets dispersed through their many tiny soil pores are less susceptible to gravity's pull, allowing the infiltrating water to spread laterally and moisten more soil volume (Fig. 3.3.).

For these reasons, a good mix of coarse and fine soil particles (eg. clay, silt, and sand) is most conducive to effective water infiltration. Sandy soils tend to absorb water very quickly because they contain few fine particles, but these soil

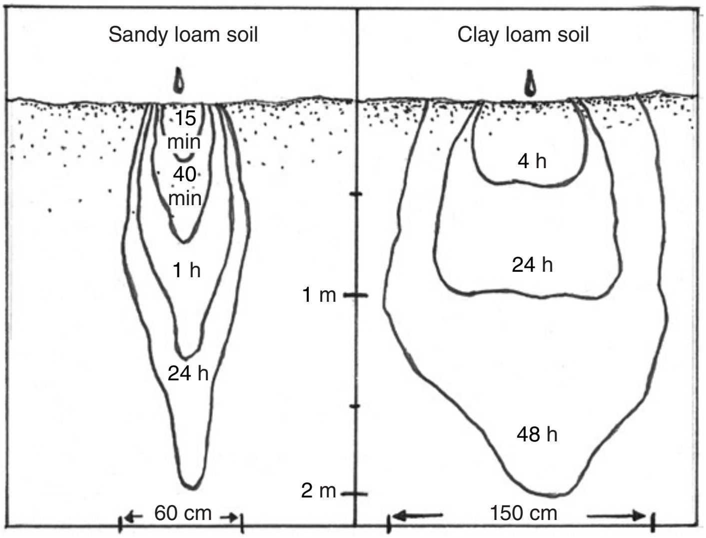

Fig. 3.3. Water infiltration in coarse-textured soil (left) and fine-textured soil (right).[8]

types are also most prone to surface sealing and compaction, which are major impediments to water infiltration.[9] A good mixture of fine particles and porosity can be approximated beneficially by incorporating organic matter into the soil profile.[10] Because it tends to be very physically heterogeneous, organic matter creates both small and large pores which are helpful in promoting infiltration and soil water storage.

It is important to maximize surface infiltration on rainfed farms so that the soil is able to capture as much water as possible during rain events. Practices designed to improve infiltration capacity are described in Part 2. The dynamics of soil infiltration are also relevant in the design of irrigation and rainwater harvesting systems, where infiltration patterns can be used to optimize the spacing of planted beds, basins and furrows. These topics are covered in Chapters 7 (Rainwater Harvesting) and 10 (Irrigation).

Box 3.1. Soil type/soil texture

Soil is formed by the gradual weathering of mineral rock combined with the deposition of organic matter. There are several different systems used to classify soils, each of which is based on a wide array of physical, biological and chemical properties that make up a vast continuum of soil characteristics. For the purposes of this publication, it is especially useful to make a distinction between different *textures* of soil, determined by the relative proportion of clay, silt, and sand particles.

- *Clay* particles are very fine and adhere strongly to water; clay soils become sticky and malleable when wet.
- *Silt* particles are only slightly larger than clay, and have a floury texture when dry.
- *Sand* particles are the largest, so sandy soils have a gritty texture.

Continued

Box 3.1. Continued.

- *Loam* is the general term for soils that contain moderate quantities of all three particle sizes. For example, sandy loam is over 50% sand, but still contains both clay and silt. A balanced loam soil made up of roughly 40% sand, 40% silt and 20% clay is considered to be the ideal texture for growing plants.[11]

The general texture of field soils can be determined by rolling a handful of wet soil around in the hand and following the decision tree shown in Fig. 3.4.

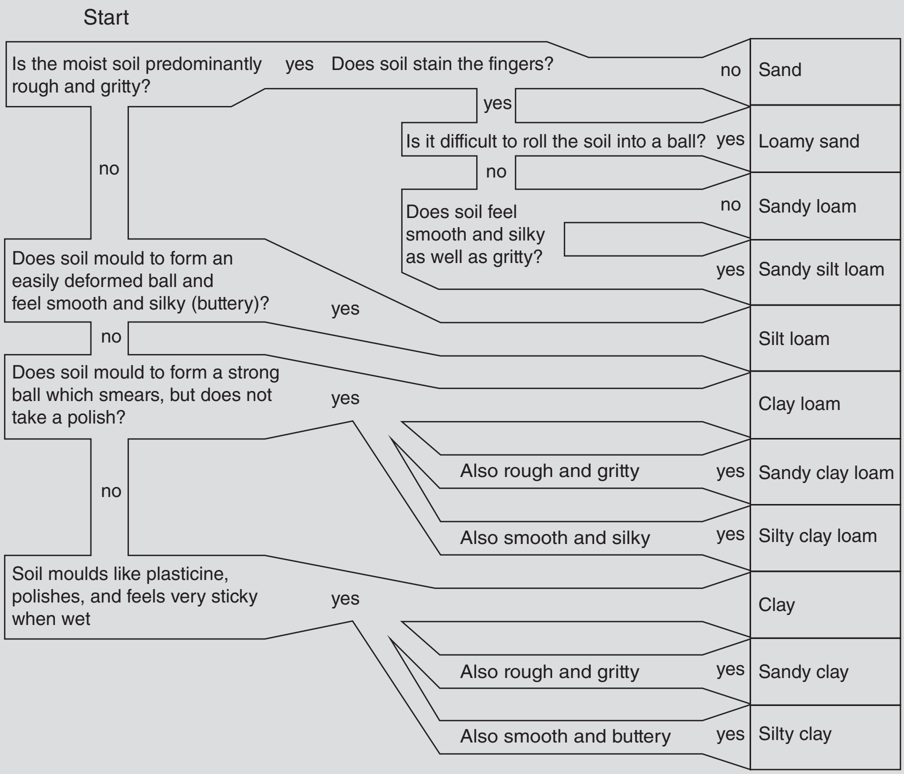

Fig. 3.4. Decision tree for determining soil texture.

Soil Water Storage

Soil acts as a dynamic water storage reservoir, absorbing water from rain and/or irrigation (and in some cases, capillary rise) and storing it for later use by plants. During dry periods, water stored in the soil is drawn upon to protect plants from the harmful effects of water stress. The soil's ability to store water is therefore critical to enhancing resilience and promoting a good crop yield.

The volume of water stored in a particular volume of soil at any given time is known as its *soil water content*, and the maximum amount of water that could potentially be contained is known as its *water holding capacity*.

Soil water content

Soil water content (commonly abbreviated as SWC) is simply a measure of the absolute quantity of water present in a set quantity of soil at any one time. Soil is made up of solids, air and water, and this term quantifies only the water portion. Soil water content is most often expressed as a percentage: the weight (or volume) of water present as a percentage of the combined weight (or volume) of the soil sample. It is also sometimes expressed as a depth of water in millimeters (mm) present per meter (m) of soil depth. Soil water content is easily determined using soil moisture sensors or neutron/time domain reflectometry (TDR) probes if these are available.[13] In the absence of this equipment, soil moisture can also be determined through the gravimetric method or estimated using the feel method.

In the gravimetric method (Fig. 3.5), the weight of a wet soil sample is compared with the weight of the same sample after complete drying in an oven set to 105°C.[14] In hot, dry climates, the soil can also be dried by spreading it out thinly in a protected area under direct sunlight for 4–8 hours.[15]

Equation 3.1[16]

$$SWC\,(\%wt) = \frac{(Wet\ sample\ weight - Dry\ sample\ weight)}{(Dry\ sample\ weight - Container\ weight)} \times 100\%$$

Where weight/mass values are expressed in grams (g), and the soil water content (SWC) is expressed as a percentage of the total sample.

This provides us with the percentage moisture by weight (m/m, grams of water per gram of soil), but most irrigation calculations are performed based on percentage moisture by volume (v/v, liters of water per liter of soil). In order to make the conversion, the weight result of Eqn 3.1 is multiplied by the soil's *bulk density*, that is, the total mass of all its particles per unit volume of dry soil, including air spaces. The approximate bulk density of common soil types is presented in Table 3.2. Density is most commonly expressed in grams per cubic centimeter of soil.

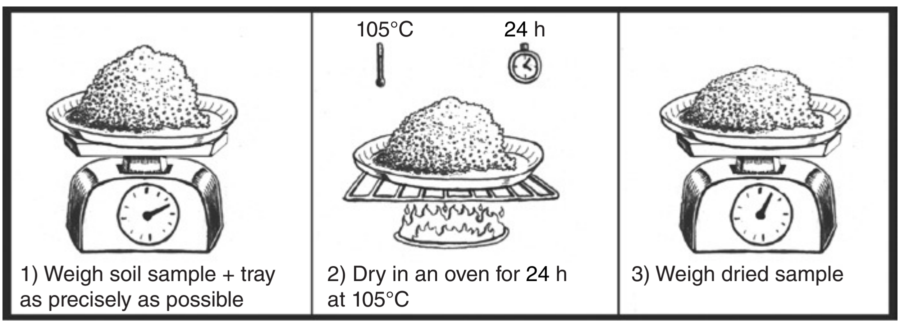

Fig. 3.5. Gravimetric method for determining soil water content.

Table 3.2. Approximate bulk density of various soil textures.[17]

Soil texture	Bulk density (g/cm^3)
Sand	1.65
Sandy loam	1.5
Loam	1.4
Clay loam	1.35
Silty clay	1.3
Clay	1.25

Equation 3.2[18]

$$SWC(\%vol) = SWC(\%wt) \times \rho$$

Where ρ is the soil's bulk density, in grams per cubic centimeter (g/cm^3), and soil water content (SWC) values are expressed as percentages.

When precise scales or ovens are not available, the 'feel method' can be used to estimate the water content of a soil sample. While this method is highly imprecise, it is widely used by farmers because it provides on-the-spot measurements without sophisticated equipment.

In the feel method, a handful of soil is worked around in the hand and various manual tests are applied: making a ball, leaving a fingerprint, rolling the soil out into a ribbon, etc. The feel method becomes more accurate with experience, once the farmer learns to recognize the feel of his or her own soil under different moisture conditions. Summarized interpretations of the feel method are presented in Table 3.3. In this table, soil water content is expressed as a percentage of total available water at field capacity (i.e. column 'Available soil moisture (%)'), which is explained later in this chapter.

Water holding capacity

While soil water content gives us an idea of how much water is stored in the soil at a specified time, it is also pertinent to know how much water the soil is capable of holding: its *water holding capacity*. This value relates directly to the physiological properties of the soil that govern its ability to retain water within its pores after natural drainage due to gravity has taken place. Water holding capacity can be visualized as the equivalent to the amount of water left in a soaked sponge after it has stopped dripping. Water delivered beyond the water holding capacity will no longer be absorbed by the soil.

Soil water holding capacity (commonly abbreviated as WHC) is most influenced by soil texture and organic matter content (Fig. 3.6). The size, structure and distribution of soil particles determine the quantity and size of soil pores where water will be allowed to accumulate. The combined volume of the many small pores in a clay soil (40–55% of total soil volume) is generally larger than the combined volume of the fewer, larger pores present in a sandy soil (30–40% of total soil volume), and the large pore size of sandy soils allows for water to

Table 3.3. Feel method for estimating soil water content.[19]

Guidelines for estimating soil moisture conditions				
	Feel and appearance of soil			
Available soil moisture (%)	Coarse texture – fine sand and loamy fine sand	Moderately coarse texture sandy loam and fine sandy loam	Medium texture – sandy clay loam, loam, and silt loam	Fine texture – clay, clay loam, or silty clay loam
0–25	Dry, loose, will hold together if not disturbed, loose sand grains on fingers with applied pressure	Dry, forms a weak ball, aggregated soil grains break away easily from soil	Dry, soil aggregations break away easily, no moisture staining on fingers, clods crumble with applied pressure	Dry, soil aggregations easily separate, clods are hard to crumble with applied pressure
25–50	Slightly moist, forms a very weak ball with well-defined finger marks, light coating of loose and aggregated sand grains remain on fingers	Slightly moist, forms a weak ball with defined finger marks, darkened color, no water staining on fingers, grains break away	Slightly moist, forms a weak ball with rough surfaces, no water staining on fingers, few aggregated soil grains break away	Slightly moist, forms a ball, very few soil aggregations break away, no wet stains, clods flatten with applied pressure
50–75	Moist, forms a weak ball with loose and aggregated sand grains on fingers, darkened color, moderate water staining on fingers, will not form a ribbon	Moist, forms a ball with defined finger marks. Very light soil/ water staining on fingers. Darkened color, will not stick	Moist, forms a ball, very light water staining on fingers, darkened color, pliable, forms a weak ribbon between thumb and forefinger	Moist, forms a smooth ball with defined finger marks, light soil/water staining on fingers, ribbons between thumb and forefinger
75–100	Wet, forms a weak ball, loose and aggregated sand grains remain on fingers, darkened color, heavy water staining on fingers, will not ribbon	Wet, forms a ball with wet outline left on hand, light-to-medium water staining on fingers, makes a weak ribbon between thumb and forefinger	Wet, forms a ball with well-defined finger marks, light to heavy soil/ water coating on fingers, ribbons between thumb and forefinger	Wet, forms a ball, uneven medium to heavy soil/ water coating on fingers, ribbons easily between thumb and forefinger
Field capacity (100%)	Wet, forms a weak ball, moderate to heavy soil/water coating on fingers, wet outline of soft ball remains on hand	Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking, medium to heavy soil/ water coating on fingers	Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking, medium to heavy soil/water coating on fingers	Wet, forms a soft ball, free water appears on soil surface after squeezing or shaking, thick soil/water coating on fingers, slick and sticky

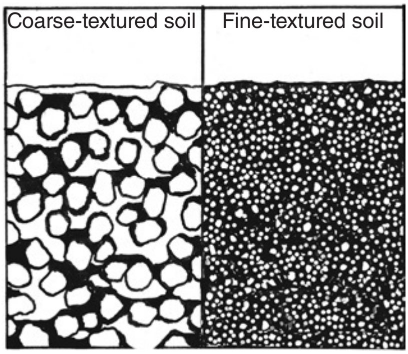

Fig. 3.6. Water retention in coarse- and fine-textured soils.

drain away more easily through the effects of gravity.[20] For these reasons, clay-rich soils have a much higher water holding capacity than sandy soils.

Organic matter content is positively correlated with water holding capacity because organic matter particles tend to be of varying texture and size, and have a strong affinity for water. Compaction negatively affects water holding capacity because it reduces the pore size by pressing soil particles together.

Determining water holding capacity

The simplest method used to determine the water holding capacity of a given soil is through the direct measurement of a representative sample collected in a container:[21]

1. Find a suitable container for the sampling: it should be opaque and water-tight, with a capacity of 5–15L
2. Pierce holes in the bottom of the container and cover it with mesh or another porous material (take care that the holes are not big enough to let the soil spill out).
3. Fill the container to 80% full with field soil. If possible, the soil should be taken directly from undisturbed soil as a core sample, or added as loose soil then compacted in the container until it can be considered to be representative of field conditions.
4. Add water to the top of the container until it begins to drain out of the holes in the bottom. Continue to add water until the soil is uniformly wet. This may take a few minutes.
5. When water starts pooling on the surface, cover the container with plastic in order to prevent evaporation. Wait for all the excess water to drip out the bottom of the container.
6. When no more water can be observed leaving the bottom of the container and there is no surface pooling, the soil has reached its water holding capacity. The soil sample's water content can now be determined using the gravimetric method described above.

The soil water content of this sample is considered the representative water holding capacity of the field area from which it was unearthed. Different fields may have distinct soil water holding capacities.

Like soil water content, soil water holding capacity is most often represented as a percentage by volume of soil:

Equation 3.3 (identical to Eqn 3.1)

$$WHC(\%wt) = \frac{(Wet\ sample\ weight - Dry\ sample\ weight)}{(Dry\ sample\ weight - Container\ weight)} \times 100\%$$

Equation 3.4 (identical to Eqn 3.2)

$$WHC(\%vol) = WHC(\%wt) \times \rho$$

Where WHC is the water holding capacity and ρ is the soil's bulk density, listed in Table 3.2.

The importance of soil water holding capacity

In a context where water inputs are limited, improvements in soil water holding capacity will lead to increased resilience in the face of frequent dry spells. Promoting water holding capacity also helps to minimize water loss to deep percolation and evaporation, leaving more of the water budget available to support plant growth. The combined effect is healthier, more robust plants that provide better yields.

Practices designed to improve soil water holding capacity are described in Part 2. Water-holding-capacity values are also used to calibrate water-delivery methods, described in Part 3.

While it is useful to promote water holding capacity to enhance green water storage, it is also vital to guarantee that soil has adequate drainage so that air exchange can take place at the root level. See Chapter 11 for more information about drainage.

Field capacity and soil saturation

When the concept of water holding capacity is extended to the whole field or plot, it becomes known as *field capacity* (commonly abbreviated as FC).[22] A plot that is at field capacity contains the maximum possible amount of water that can be retained in the soil, after drainage due to gravity is complete. A sandy soil that had been irrigated to field capacity could contain only about 15% water by volume, whereas a clay-rich soil would be

Table 3.4. Sample values of field capacity, wilting point, and available water at field capacity for various soil textures.[23]

Soil texture	Field capacity (%)	Wilting point (%)	Available water (%)
Sand	15	7	8
Sandy loam	21	9	12
Loam	31	14	17
Clay loam	36	17	19
Silty clay	10	19	21
Clay	44	21	23

nearly 40% water at that point. The terms 'water holding capacity' and 'field capacity' are sometimes used interchangeably and both are expressed as percentage values. Field capacity values will depend on both soil and plant factors, and sample values found in the literature can vary depending on the method used to measure it. Some sample values of field capacity for different soil textures are given in Table 3.4.

Adding extra water after the field capacity is reached results in soil *saturation*. Saturation should be avoided because saturated soil layers are more likely to leach nutrients and other beneficial elements into the subsoil, where they are no longer available to plant roots. If sustained, saturated soil conditions will harm plant roots and inhibit crop development.[24]

Permanent wilting point and available water

Not all of the water retained in soil pores is available to the plant. Below a certain level of soil moisture, the force that would be required to extract the remaining water from the soil is greater than the extraction force that can be exerted by the plant's roots.[25] This critical point of minimum accessible soil moisture is known as the *permanent wilting point* (commonly abbreviated as WP): below this level, the plant will no longer have access as sufficient soil water and irreversible wilting will result. Wilting point values vary according to specific soil properties and plant factors. Exact figures are difficult to obtain, but the approximate wilting point ranges of different soil textures can provide sufficient information to inform water management decisions. Indicative values are presented in Table 3.4.

Because water content below the wilting point is not accessible by the plant, this portion can be deducted from the soil water content value. The term *available water* is used to designate only the quantity of water retained in the soil *above* the wilting point value (SWC-WP). These distinctions are especially relevant in irrigation calculations, where the water content of soil is often expressed as a percentage of the total available soil water at field capacity (see Fig. 3.7). Sample values of available water at field capacity for different soil types are presented in Table 3.4.

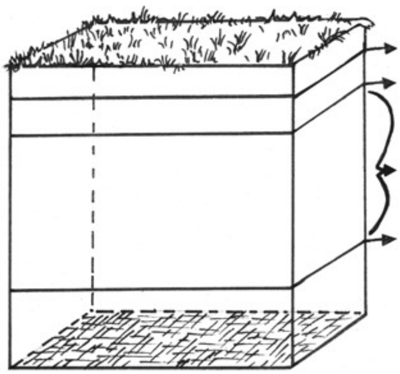

Fig. 3.7. Concepts in water availability (with sample values).[26]

Available water within the *rooting depth* of the chosen crop is most important – this is the depth of soil that contains most (~80%) of the plant roots at the current growth stage. Rooting depths of mature crop plants vary widely between shallow rooted crops (e.g. onion) at 30 cm and deep-rooted varieties (e.g. sunflower) that can descend to 150 cm in deep soil.[26]

Soil water availability is strongly influenced by water quality. Low-quality or saline water, in the same quantity, will contain lower absolute values of available water than fresh, uncontaminated water. This is because high salt concentrations oblige plant roots to exert more force to extract the water molecules they require. Water quality is discussed further in Chapter 12.

Soil fertility

Soil fertility affects the degree to which water will be effectively used by the plant. Water and nutrients in the soil–plant interface are interdependent: nutrients are extracted from decaying plants and organic matter by soil water, which in turn transports them through the roots and into the tissues of plants where they can be used in metabolic functions. In experiments on rainfed smallholder farms, the most significant improvements in crop yield are obtained when water availability is enhanced in conjunction with improvements in soil fertility.[28]

Plants require a good supply of both *macronutrients* and *micronutrients* to develop. Macronutrients are so called because they are needed in larger amounts: these include nitrogen, potassium, and phosphorous (as well as 'secondary' nutrients calcium, magnesium, and sulfur). Of these, nitrogen is required in the highest quantity. Micronutrients are only needed in trace amounts by the plant, but they are nonetheless crucial. Some important micronutrients include: boron, iron, manganese, molybdenum, chloride, nickel, copper, and zinc.

Nutrients are added to the soil by various mechanisms, the most common of which are: (i) the release of nutrients from decomposing plant residues and manure (organic matter) in the soil; (ii) the application of synthetic fertilizers; and (iii) nitrogen fixing-plant species.

Release of nutrients from plant residues and manure

Nutrients are returned to the soil through the breakdown of plants, animal wastes, and other organisms as they decay in and on the ground. Plant residues and manures are important storehouses of nutrients that should not be removed from the field environment. The cycling of organic matter is covered in more detail in Chapter 6.

Application of synthetic fertilizers

The use of synthetic (also known as mineral/chemical/inorganic) fertilizers has increased significantly in the past few decades, though use on small rainfed farms is still low.[29] These provide a good, predictable supply of nutrients, and their use can be calibrated to provide the right nutrients at the right time. However, these products are costly inputs for poor farmers, and their use does little to enhance the health of the soil. Fertilizer use is also a major cause of water pollution worldwide. These products are therefore most useful as a targeted supplement and not as the primary nutrient supply.

Nitrogen-fixing plants

Certain species of plants are called 'nitrogen fixing' because they have a special relationship with soil bacteria that are capable of fixing atmospheric nitrogen (in the air) into the soil. These bacteria form small nodules on the roots of nitrogen-fixing plant species. The nitrogen that they capture from the air is made available to the soil when these plants die and their residues decay on the field. Nitrogen-fixing plants are used as part of a crop rotation, or intercropped with the main crop to enhance the nutrient content of the soil. Legumes, including species of beans, peas, lucerne (alfalfa), clover, and soybean are nitrogen-fixing plants commonly used in farming.

Though soil fertility is outside of the scope of this book, it is important to recognize the importance of key nutrients in enhancing water productivity and producing good yields. Water and nutrients are the most essential requirements of any farm system, and the loss of soil nutrients is a major contributing cause of land degradation.

Further reading – Nutrient management

Plant and crop production, in *Soils, Crops and Fertilizer Use*, an online manual produced by the University of Waikato in the Humanity Development Library (New Zealand Digital Library). Available at: http://www.nzdl.org/gsdlmod?a=p&p=about&c=hdl

References

[1] Nair, P., 1993. *An Introduction to Agroforestry*. Dordrecht, The Netherlands: Kluwer Academic Publishers, p. 62.

[2] African Conservation Tillage Network (ACT) & International Institute of Rural Reconstruction (IIRR), 2005. What is conservation agriculture?, in *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa*. Nairobi: IIRR.

[3] International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), 2009. Agriculture at a Crossroads: East and South Asia and the Pacific (ESAP) Report, B. McIntyre *et al*., eds. Washington, DC: Island Press, p. 46.

[4] Adapted from ACT & IIRR, 2005. What is conservation agriculture?, in *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa*. Nairobi: IIRR.

[5] Ibid.

[6] Ali, M.H., 2010. Soil–water–plant atmosphere relationship, in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, p. 373.

[7] Ibid.

[8] Adapted from Mohamed S. Alhammadi & Ali M. Al-Shrouf, 2013. Irrigation of sandy soils, basics and scheduling, in Dr Aakash Goyal, ed., *Crop Production*, ISBN: 978-953-51-1174-0, InTech, DOI: 10.5772/55117. Available at: http://www.intechopen.com/books/crop-production/irrigation-of-sandy-soils-basics-and-scheduling [Accessed November 9, 2013].

[9] Food and Agriculture Organization of the United Nations (FAO), 1993. Soil tillage in Africa: needs and challenges. *fao.org*. Available at: http://www.fao.org/docrep/t1696e/T1696e00.htm#TopOfPage [Accessed November 7, 2015].

[10] Bot, A. & Benites, J., 2005. *The Importance of Soil Organic Matter*. Rome: FAO, p. 36.

[11] Ali, M.H., 2010. Soil: a media for plant growth, in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, p. 121.

[12] Anon, Farm Efficiency Hub – Library Contents. *adlib.ac.uk*. Available at: http://www.adlib.ac.uk/ghg/doccontent.eb?docGuid=85641&id=85717 [Accessed November 7, 2015].

[13] Ali, M.H., 2010. Soil: a media for plant growth, in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, pp. 168–175.

[14] Ibid. p. 154.

[15] Perrier, E.R. & Salkini, A.B., 1991. Soil water measurement, in *Supplemental Irrigation in the Near East and North Africa*. Dordrecht, The Netherlands: Springer, p. 124.

[16] Ibid. p. 123.

[17] Adapted with permission from Burton, M., 2010. *Irrigation Management: Principles and Practices*. Wallingford, UK: CABI, p. 128.

[18] Ali, M.H., 2010. Soil: a media for plant growth, in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, p. 115.

[19] Adapted from United States Department of Agriculture (USDA), Estimating soil moisture by feel and appearance. *cdpr.ca.gov*, p. 6. Available at: http://www.cdpr.ca.gov/docs/county/training/inspprcd/handouts/soil_moist_feel_test.pdf [Accessed May 3, 2012].

[20] Ali, M.H., 2010. Soil: a media for plant growth, in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, p. 150.

[21] Ibid. p. 151.

[22] Ibid. p. 149.

[23] Adapted with permission from Burton, M., 2010. *Irrigation Management: Principles and Practices*. Wallingford, UK: CABI, p. 128.

[24] Bot, A. & Benites, J., 2005. *The Importance of Soil Organic Matter*. Rome: FAO, p. 12.

[25] Ali, M.H., 2010. Soil: a media for plant growth, in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, p. 124.

[26] Adapted from Garcia-Tejero, I. *et al*., 2011. *Water and Sustainable Agriculture*. Dordrecht, The Netherlands: Springer, p. 49.

[27] Anschütz, J. *et al*., 2003. *Water Harvesting and Soil Moisture Retention*, M. Nederlof & J. Anschütz, eds. Wageningen, The Netherlands: Agromisa Foundation, p. 19.

[28] Barron, J., 2004. *Dry Spell Mitigation to Upgrade Semi-arid Rainfed Agriculture*. Stockholm: Department of Systems Ecology, Stockholm University.

[29] Wani, S.P. *et al*., 2009. Rainfed agriculture – past trends and future prospects, in S.P. Wani *et al*., eds, *Rainfed Agriculture: Unlocking the Potential*. Wallingford, UK: CABI.

4 Plants and Water

Water availability is a principal limiting factor to plant development and crop yield. In laboratory studies, the total dry matter production of crop plants has been shown to have a linear relationship to water uptake: the more water used, the more yield produced, up to the point where the full plant water requirement is met.[1]

Water plays several roles in plant development and crop production:

1. Water is the principal transport mechanism for moving essential nutrients, minerals and dissolved carbohydrates through plant tissues. Water moves from regions of low to high potential, pulling it from the soil into roots, upward through plant tissues, and out through the leaf surface into the atmosphere in a continuous sequence driven by transpiration. As it moves through the plant, water delivers essential elements from roots to shoots and leaves where they are used in plant metabolic processes.

2. Water is a critical reactant in chemical reactions occurring in plant cells. Perhaps the most important of these reactions is photosynthesis, through which solar energy is converted into plant biomass.

3. Water content produces *turgor pressure* within individual plant cells, which is responsible for plant growth and structure (Fig. 4.1). One of the first visible signs of lack of water is a reduction in turgor pressure, which causes stems and leaves to sag or fold as they wilt. Plants will also shed leaves as they react to decreases in turgor pressure, in an effort to reduce the cell surface area that requires support.[2]

4. In a related process, water availability affects the opening and closing of leaf stomata (Fig. 4.2), tiny surface pores that regulate the intake of carbon dioxide (CO_2) and the release of water vapor into the atmosphere. Stomatal opening is governed by the turgidity of pairs of guard cells that bend under high water conditions causing the stoma to open, and collapse together to close stomatal openings (slowing transpiration and photosynthesis) in times of water stress.

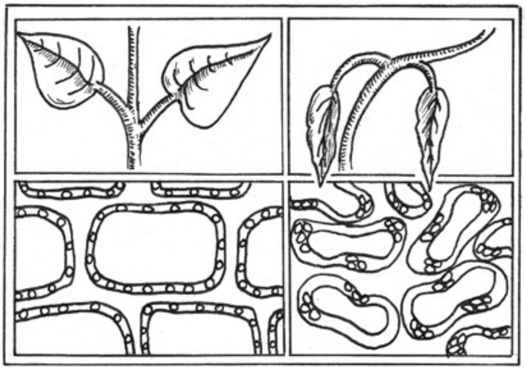

Fig. 4.1. Turgor pressure.

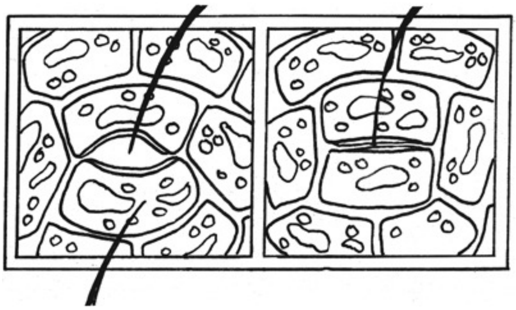

Fig. 4.2. Opening and closing of stomata on the leaf surface.

Plant Water Use

As stated in Chapter 3, over 99% of the water that enters a plant is ultimately transpired into the atmosphere. The quantity of water "used" by a given plant is therefore considered to roughly equal its *transpiration rate* (T). In practice, however, transpiration is difficult to measure independently from the *evaporation rate* (E) of the soil immediately surrounding the plant, because the processes occur simultaneously. These two quantities are thus often combined to designate the *evapotranspiration rate* (ET) of a plant. ET values are used to communicate the water usage rate of plants.

Crop water requirement is the crop-specific ET rate, often expressed as ET_c. The full ET_c rate is reached only under optimum growing conditions and ample soil water, and a plant that is supplied with its full crop water requirement will theoretically produce the maximum possible yield in a given context.[3] Field conditions usually deviate from the ideal, so actual water use in most cases will be less than the full ET_c rate. The actual ET rate under current growing conditions is expressed as ET_a (actual evapotranspiration rate).

ET_c and ET_a values are usually expressed as a depth of water used per day (mm/day). *Seasonal crop water requirement* is the total amount of water required by a given crop over its complete growing season, from seed to harvest (mm/season or simply mm). The approximate seasonal crop water requirement of some common field crops is presented in Table 4.4 at the end of this chapter.

Determining Crop Water Requirement

Factors affecting evapotranspiration

Plant evapotranspiration rate is difficult to determine with a high degree of accuracy because it depends on a range of context-specific factors related to plant type, weather, soil, and management practices. For example, actual evapotranspiration from the same plant species will be higher in warm, dry climates than in cloudy, humid ones. Evapotranspiration also varies widely between stages of plant development: an adult fruiting crop will require considerably more water than a young seedling.

Some factors that influence evapotranspiration rate are outlined in Table 4.1.

Methods for determining crop evapotranspiration

There are several methods used to estimate crop-specific values of ET. These include both direct methods, which measure evaporation and transpiration at the

Table 4.1. Factors influencing evapotranspiration (ET).[4]

Factors influencing ET rate	High ET rate	Low ET rate
Leaf area	Large leaves	Small or curled leaves
Soil moisture	Wet soil	Dry soil
Solar radiation	High	Low
Day length	Long	Short
Temperature	Hot	Cool
Wind speed	High	Low
Humidity	Dry	Humid
Mulching	None	Good
Soil salinity	Low	High
Shading	None	High
Irrigation[a]	Good	Poor or none
Fertilization[a]	Good	Poor or none
Control of pests and disease[a]	Good	Poor or none

[a]In this last group of management-related factors, all actions that tend toward optimum conditions will have a positive effect on ET rates.

field level with the use of moisture-sensing equipment, and indirect methods, which approximate these values based on weather data, crop type, and a standardized *reference evapotranspiration* (ET_o) value. Both approaches have their drawbacks: direct methods can be highly technical and expensive, and indirect methods tend to require detailed climate data that are not always easy to find.[5]

This section describes methods used to approximate ET values to aid in making water management decisions. For simplicity, only one direct method (lysimeter method) and one simplified indirect method (calculation using climate data and typical ET_o values) are presented here, but several other methods exist in each category. Those who wish to proceed with a more precise ET measurement are encouraged to consult with local agricultural agencies, which may have the expertise, data and/or instruments necessary for more detailed methods not included here.

Direct measurement using a lysimeter

A lysimeter is a simple device that allows for the replication of field conditions within a sealed container, so that water movement in and out of the sample (through drainage, evaporation, and transpiration) can be measured. There are two types of lysimeter: (i) weighing lysimeters, which are attached to a scale that measures water flows by weight; and (ii) drainage lysimeters (Fig. 4.3),

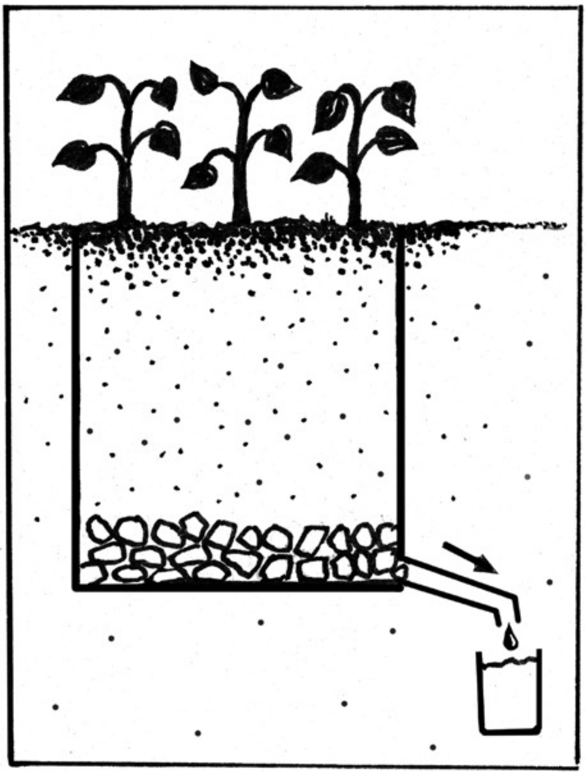

Fig. 4.3. Drainage lysimeter.[6]

which quantify water flows leaving the unit by volume. In both cases, ET can be determined directly by monitoring the water input/output values after a certain time interval. The most precise weighing lysimeters can produce data for short time periods, down to 10 min intervals, but for basic water management planning purposes, weekly or monthly figures are usually sufficient.[7] Lysimeters can be erected on site without specialized labor, but they are expensive to construct and are not easily movable. Once installed, however, lysimeters can be very useful for monitoring ET rates, deep percolation, and surface runoff. They can also be used to test out the water requirement of new crop cultivars before introducing them on a large scale.

Lysimeters must be very precisely installed if they are to be accurate: conditions within the apparatus should be representative of field conditions in terms of rainfall, solar exposure, crop (and weed) density, soil stratigraphy and compaction.[8] Lysimeters are usually installed in the middle of the field. ET is measured by monitoring the water balance in and out of the device:

Equation 4.1

$$ET_a = Water\ IN - Water\ OUT + \Delta\ Soil\ moisture$$

Where ET_a is the actual ET of the crop grown within the device, Water IN is the water received either through irrigation or rainfall, Water OUT is the water escaping through drainage, and Δ Soil moisture is the change in soil water content (SWC) over the measurement period (SWC_{before} – SWC_{after}). If soil water content increased during the sampling period, Δ Soil moisture will be a negative number.

Indirect estimation using climate data

Because direct measurement can be cumbersome, indirect methods are more widely used for calculating ET. Indirect methods involve three steps:

1. Determination of a *potential evapotranspiration* (ET_o) value based on a theoretical model crop growing in reference climatic conditions.
2. Determination of the crop-specific coefficient, K_c.
3. Calculation of the specific evapotranspiration rate of the chosen crop (ET_c) by multiplying the reference evapotranspiration (ET_o) by the crop coefficient (K_c).

Both ET_o and K_c are determined according to local climate and crop information. Local values of each may be available from agricultural extension offices, universities, or farmers' groups. Alternatively, they can be estimated using the methods provided below. These estimates are much less accurate than local information, but are helpful in making preliminary evaluations when more specific data are hard to come by.

1. ESTIMATING ET_o. Reference evapotranspiration (ET_o) is the evapotranspiration rate of a theoretical reference crop with idealized characteristics: uniform height, extensive leaf coverage shading the bare soil, optimal water and nutrient conditions, and vigorous growth.[9]

ET_o is calculated based on a range of specific local climate variables. Some equations often used to calculate local ET_o include the *Penman–Monteith* formula (and its FAO-recommended variant) and the *Blaney–Criddle* method. These equations incorporate a wide range of precise climate variables, and it can be difficult for the individual farmer to acquire all the data necessary to use them accurately. The further reading box at the end of this section provides a reference that outlines ET_o and ET_c calculation methods in detail.

In the interest of simplicity, some sample ET_o values are provided in Table 4.2. These are only rough estimates – farmers should seek to find appropriate values for their region. ET_o values change throughout the year, so specific monthly or weekly values are most useful.

2. FINDING K_c. The next step in the indirect method for calculating crop water requirement is the determination of K_c, the crop coefficient. K_c is a unitless value used to relate the evapotranspiration of the chosen crop to that of the reference crop, based on their differences in size, canopy resistance, albedo, and ground cover.

Because a plant's water requirement changes throughout its life cycle, K_c values are often divided into specific values for each stage of plant development. For example, the K_c of sorghum is only 0.35 during the initial stages of seedling development, becomes 0.75 during crop development, increases again to 1.1 during the mid-season where its growth is most vigorous, then falls off to 0.65 near the end of its growing season.[11] K_c values above 1 indicate growth stages where the crop requires more water than the reference crop. Usually, values for K_c are found in reference literature. Sample K_c values for several common field crops are provided in Table 4.3.

In Table 4.3, the *initial stage* refers to the period between planting date and approximately 10% ground cover by surface area. The *crop development stage* runs from 10% ground cover to effective full cover, which is reached for some crops at 70–80% ground cover, the start of flowering, or when leaves in adjacent row crops begin to intermingle. The *mid-season stage* refers to the period after effective full cover is reached until the plant reaches full maturity[13]. The mid-season stage demands the most water because it includes the bulk of grain-filling and fruit development.[13] The *late season stage* covers the period between full maturity and harvest. This last stage is relatively brief in

Table 4.2. Typical potential evapotranspiration (ET_o) values (mm/day).[10]

	Mean daily temperature		
Climatic zone	Low (less than 15°C)	Medium (15–25°C)	High (more than 25°C)
Desert/arid	4–6	7–8	9–10
Semi-arid	4–5	6–7	8–9
Sub-humid	3–4	5–6	7–8
Humid	1–2	3–4	5–6

Table 4.3. Sample crop coefficient (K_c) values.[12]

Crop	K_c values				Total growing period (days)
	Initial stage	Crop development stage	Mid-season stage	Late season stage	
Aubergine (eggplant)/ tomato	0.45	0.75	1.15	0.8	130–140/135–180
Barley/oats/ wheat	0.35	0.75	1.15	0.45	120–150
Bean, green	0.35	0.7	1.1	0.9	75–90
Bean, dry	0.35	0.7	1.1	0.3	95–110
Cabbage/carrot	0.45	0.75	1.05	0.9	120–140/100–150
Cotton/flax	0.45	0.75	1.15	0.75	180–195/150–220
Cucumber/ squash	0.45	0.7	0.9	0.75	105–130/95–120
Grain/small	0.35	0.75	1.1	0.65	150–165
Groundnut (peanut)	0.45	0.75	1.05	0.7	130–140
Lentil/pulses	0.45	0.75	1.1	0.5	150–170
Lettuce/spinach	0.45	0.6	1.0	0.9	75–140
Maize, sweet	0.4	0.8	1.15	1.0	80–110
Maize, grain	0.4	0.8	1.15	0.7	125–180
Melon	0.45	0.75	1.0	0.75	120–160
Millet	0.35	0.7	1.1	0.65	105–140
Onion, green	0.5	0.7	1.0	1.0	70–95
Onion, dry	0.5	0.75	1.05	0.85	150–210
Pea, fresh	0.45	0.8	1.15	1.05	90–100
Pepper, fresh	0.35	0.7	1.05	0.9	120–210
Potato	0.45	0.75	1.15	0.85	105–145
Radish	0.45	0.6	0.9	0.9	35–45
Sorghum	0.35	0.75	1.1	0.65	120–130
Soybean	0.35	0.75	1.1	0.6	135–150
Sugarbeet	0.45	0.8	1.15	0.8	160–230
Sunflower	0.35	0.75	1.15	0.55	125–130
Tobacco	0.35	0.75	1.1	0.9	130–160

crops that are harvested fresh, but longer in crops harvested dry or for seed.[14] The number of days that a given crop spends in each of these four stages is climate specific: values can be found in reference literature or estimated based on local experience.

3. CALCULATING CROP WATER USE (ET_c). Once ET_o and K_c have been either calculated or estimated, it becomes possible to calculate the crop water requirement, ET_c, using the indirect method:

Equation 4.2

$$ET_c = ET_o \times K_c$$

Where ET_c and ET_o are expressed in mm/day, and K_c is unitless.

The resulting ET_c value is expressed as a depth of water used per day (mm/day), specific to the growth stage of the K_c value used. Remember that ET_c represents a maximum value for the crop evapotranspiration rate under idealized conditions: adequate water and nutrients, full sun, and best management practices. Actual evapotranspiration rate (ET_a) will be lower than ET_c when conditions are less than ideal. Nonetheless, the goal is to supply the crop with its full ET_c water demand in order to produce optimal yields.

Total seasonal crop water requirement, ET_{total}

Once values for ET_c have been determined using either a direct or an indirect method, it is possible to estimate the amount of water a crop will require over its complete growing cycle. This is done by calculating the total water required during each individual growth stage, then adding the totals together.

Equation 4.3

$$(Total\ days\ in\ stage\ 1) \times (Daily\ ET_c\ during\ stage\ 1) = ET_c\ stage\ 1$$
$$(Total\ days\ in\ stage\ 2) \times (Daily\ ET_c\ during\ stage\ 2) = ET_c\ stage\ 2$$
$$(Total\ days\ in\ stage\ 3) \times (Daily\ ET_c\ during\ stage\ 3) = ET_c\ stage\ 3$$
$$(Total\ days\ in\ stage\ 4) \times (Daily\ ET_c\ during\ stage\ 4) = ET_c\ stage\ 4$$

The total seasonal crop water requirement is the sum of the ET_c of all growth stages:

$$ET_c\ stage\ 1 + ET_c\ stage\ 2 + ET_c\ stage\ 3 + ET_c\ stage\ 4 = Total\ seasonal\ crop\ water\ requirement\ (mm/season)$$

Table 4.4 presents sample values for the seasonal water requirements of some common field crops. A range of values is provided because the actual water demand of crops will vary significantly according to local conditions and crop variety.

A worked example using the indirect method of calculating water use is provided in Box 4.1.

Further reading – Calculation of ET_o, K_c and ET_c

Irrigation Water Management Training Manual #3: Irrigation Water Needs, produced by the Food and Agriculture Organization of the United Nations (FAO). Available at: www.fao.org/docrep/s2022e/s2022e00.HTM

Table 4.4. Sample seasonal crop water requirements.[15]

Crop	Crop water requirement (mm/season)
Banana	1200–2200
Barley/oats/wheat	450–650
Beans	300–500
Cabbage	350–500
Citrus	900–1200
Cotton	700–1300
Groundnut (peanut)	500–700
Lucerne (alfalfa)	800–1600
Maize	500–800
Onion	350–550
Pea	350–500
Pepper	600–900
Potato	500–700
Rice (paddy)	450–700
Sorghum/millet	450–650
Soybean	450–700
Sugarbeet	550–750
Sugarcane	1500–2500
Sunflower	600–1000
Tomato	400–800

Water stress

Under ideal conditions, the full crop water requirement of a plant would be available at all times through the maintenance of optimum soil moisture. Under such conditions, plants would be expected to reach their full potential yield, on the condition that they also have access to adequately fertile soils and sufficient sunlight.

A plant that does not have access to its full ET water requirement at any given time is considered to be in a water deficit situation that will lead to a certain degree of *water stress*.[16] Because water is so essential to plant development, the generalized effect of water stress is a visible loss of vitality and reduced yields. Specific effects will vary according to the growth stage at which the plant experiences stress. Examples include: (i) lower germination rates; (ii) stunted growth; (iii) reduced nutrient uptake; (iv) increased vulnerability to pests and disease; and (v) reduced grain, leaf and fruit size.[17] Stress effects are not always limited to the current growth stage; often they can extend into subsequent stages as well even if water availability is restored. The severity of stress effects will depend on factors including:[18]

- crop type;
- crop variety (genotype);
- duration of stress condition;
- severity of stress condition;
- timing and frequency of stress condition;

- water quality;
- history of water stress; and
- speed of onset of water stress conditions.

Some documents define 'water stress' as a condition where soil water content drops below full field capacity. This definition ignores the fact that plants can grow well within a range of soil moisture conditions.[19] Even in carefully controlled mechanized farming where irrigation equipment and water are in abundant supply, a certain degree of soil water deficit (where soil water content drops below field capacity) is effectively unavoidable. However, soil water deficit does not always directly equate to water stress in plants, which can continue to grow and develop well as long as some degree of *readily available water* is present in the soil of the root zone (see Chapter 11). When soil moisture drops past the critical point where water is no longer readily available to the plant's root system, stress sets in. In order to produce good yields, water stress severity, duration and frequency must be kept within reasonable limits through soil and water management practices and/or irrigation water applications.

The management of water stress conditions forms the theoretical basis of the practices of supplemental and deficit irrigation, which involve the careful scheduling of water applications to mitigate the damage caused by plant water stress while using less water. Irrigation is discussed in Chapters 10 and 11.

Box 4.1. Example

The indirect method of calculating water use helps farmers and extension workers to understand how the water provided to their crops compares with the water that the crop actually requires to produce full yields.

As an example, let's imagine a farmer near Brazzaville, Congo who cultivates maize as a grain crop. Her climate category is humid and hot, so she uses an estimated ET_o value of 5 mm/day (Table 4.2). The K_c of grain maize is taken from Table 4.3 to be:

0.4	0.8	1.15	0.7
Initial stage	Crop development stage	Mid-season stage	Late season stage

From her own experience, the farmer knows that her maize crop typically spends about 25 days in the initial stage, 30 days in the crop development stage, and 45 days each in the mid-season and late-season stages. This is her estimate based on the total life cycle of the crop, which she knows is around 145 days.

She now has all the information necessary to find out how much water her maize crop would ideally require to produce its full yield.

1. She calculates the plant water requirement (ET_c) for each stage of growth:

Remember: $ET_c = ET_o \times K_c$ **(Eqn 4.2)**
Stage 1 (K_c of 0.4): ET_c = 5 mm/day × 0.4 = 2 mm/day
Stage 2 (K_c of 0.8): ET_c = 5 mm/day × 0.8 = 4 mm/day
Stage 3 (K_c of 1.15) ET_c = 5 mm/day × 1.15 = 5.75 mm/day
Stage 4 (K_c of 0.7) ET_c = 5 mm/day × 0.7 = 3.5 mm/day

Continued

Box 4.1. Continued.

Now the farmer knows how much water her plants would transpire in one day during each growth stage under ideal conditions.

2. Now she calculates the total seasonal crop water requirement from seed to harvest:

Remember: ET_{total} = days in stage 1 × ET_c stage 1 **(Eqn 4.3)**
+ days in stage 2 × ET_c stage 2
+ days in stage 3 × ET_c stage 3
+ days in stage 4 × ET_c stage 4

So in her case: Stage 1: 25 days × 2 mm/day = 50 mm
+ Stage 2: 30 days × 4 mm/day = 120 mm
+ Stage 3: 45 days × 5.75 mm/day = 259 mm
+ Stage 4: 45 days × 3.5 mm/day = 158 mm

Total crop water requirement (ET_{total}) = **587 mm/season**

Now the farmer knows approximately how much water her plants would need to be able to access in order to produce their full yield.

References

[1] O'Leary, G.J. *et al*., 2011. Rainfed farming systems, in P. Tow *et al*., eds, *Rainfed Farming Systems.* Dordrecht, The Netherlands: Springer, p. 103.

[2] Ali, M.H., 2010. Soil: a media for plant growth, in *Fundamentals of Irrigation and On-farm Water Management,* Volume 1. New York: Springer, p. 390.

[3] Allen, R.G. *et al*., 1998. Crop evapotranspiration – guidelines for computing crop water requirements. *fao.org*. Available at: www.fao.org/docrep/X0490E/x0490e00.htm [Accessed December 6, 2012].

[4] Adapted from Ali, M.H., 2010. Field water balance, in *Fundamentals of Irrigation and On-farm Water Management,* Volume 1. New York: Springer, pp. 335–336.

[5] Allen, R.G. *et al*., 1998. Crop evapotranspiration – guidelines for computing crop water requirements. *fao.org*. Available at: www.fao.org/docrep/X0490E/x0490e00.htm [Accessed December 6, 2012].

[6] Adapted with permission from Dastane, N.G., 1978. Effective rainfall in irrigated agriculture. *fao.org*. Available at: http://agris.fao.org/agris-search/search.do?recordID=XF8000065 [Accessed May 15, 2015].

[7] Ali, M.H., 2010. Field water balance, in *Fundamentals of Irrigation and On-farm Water Management,* Volume 1. New York: Springer, pp. 331–372.

[8] Ibid.

[9] Critchley, W. & Siegert, K., 1991. *Water Harvesting*. Rome: Food and Agriculture Organization of the United Nations (FAO), p. 20. Available at: http://www.fao.org/docrep/U3160E/u3160e00.HTM [Accessed December 6, 2012].

[10] Adapted with permission from Brouwer, C. & Heibloem, M., 1986. *Irrigation Water Management: Irrigation Water Needs*. Training Manual. Rome: FAO. Available at: ftp://193.43.36.92/agl/AGLW/fwm/Manual3.pdf [Accessed February 15, 2015].

[11] Brouwer, C. & Heibloem, M., 1986. *Irrigation Water Management: Irrigation Water Needs*. Training Manual. Rome: FAO.

[12] Ibid. (adapted with permission).

[13] Allen, R.G. *et al*., 1998. Crop evapotranspiration – guidelines for computing crop water requirements. *fao.org*. Available at: www.fao.org/docrep/X0490E/x0490e00.htm [Accessed December 6, 2012].

[14] Ibid.

[15] Adapted with permission from: (i) Brouwer, C. & Heibloem, M., 1986. *Irrigation Water Management: Irrigation Water Needs*. Training Manual. Rome: FAO. Available at: ftp://193.43.36.92/agl/AGLW/fwm/Manual3.pdf [Accessed February 15, 2015]; and (ii) Critchley, W. & Siegert, K., 1991. *Water Harvesting*. Rome: FAO. Available at: http://www.fao.org/docrep/U3160E/u3160e00.HTM [Accessed December 6, 2012].

[16] Ali, M.H., 2010. Soil–water–plant atmosphere relationship, in *Fundamentals of Irrigation and On-farm Water Management,* Volume 1. New York: Springer, pp. 383–388.

[17] Ibid.

[18] Ibid.

[19] Ibid.

5 Climate Outlook

The earth's climate is changing. Farmers, especially those working on rainfed projects in the drier parts of the world, have likely already felt the effects of global climate change, in the form of shifted rainy seasons, heavier storms, or extended dry periods during the growing season. In fact, smallholder farmers and laborers working on rainfed farms in the developing world are among those most directly affected by global climate change. At the same time, the ingenuity and traditional environmental knowledge that small farmers possess will be a key tool for adaptation to new climate realities.

Changes in water availability – in the form of rainfall patterns, green water storage, surface water flows, and water quality – are some of the most visible effects of climate change. Because the unpredictability of these resources is only expected to increase in as time goes by, it is important to learn to anticipate and adapt to new conditions before their effects become too pronounced.

The realities of climate change include a huge variety of interwoven social, environmental, and financial impacts. Details of these impacts can be found within the vast compendiums of research compiled every few years by the scientists of the Intergovernmental Panel on Climate Change (IPCC). Some of the effects of global climate change highlighted by the IPCC that are most likely to impact agrarian communities in the tropics include:

- Rising temperatures – Global average temperatures have increased dramatically in the past decades, and are expected to continue to rise. Along with this rise in average temperatures comes an increase in peak temperatures, which means hotter daytime temperatures and fewer cold days.[1]
- Rising sea levels – Increased temperatures lead to the melting of sea ice and an overall rise in the level of the oceans. Global average sea levels rose by nearly 20 cm between 1901 and 2010. Rising sea levels contribute to increasing salinity in coastal aquifers, lakes, and rivers.[2]

- Increased atmospheric CO_2 – Recent decades have seen a steep rise in atmospheric CO_2. Technically, increased CO_2 is good for plant growth, since plants consume it during photosynthesis. However, this is not reflected in global staple crop yields, which have been declining due to a combination of other factors linked to climate change.[3]
- Increased/decreased rainfall amount – Rainfall patterns have changed substantially over the past 100 years, causing increases in average precipitation in some regions and decreases in others. Overall, precipitation has increased in eastern North and South America, Northern Europe, and northern and central Asia, and decreased in the countries of the Sahel, the Mediterranean, sub-Saharan Africa, and parts of Southern Asia.[4]
- More intense rainfall and increased frequency of extreme events – The intensity of rainfall (and the proportion of rains that occur as heavy storms) has increased in the last 50 years and should continue to increase. Worldwide, the area of land affected by drought has increased, as has the intensity of tropical cyclones.[5]
- Loss of biodiversity – *Biodiversity*, a measure of the number and diversity of species of plants, animals, insects, fungi and microorganisms present on earth, is intricately tied to climate. Biodiversity has been steeply declining in the past 100 years and is expected to decline ever faster in the future. Biodiversity is one of the most important determinants of environmental resilience, so a loss of biodiversity further increases the vulnerability of farm ecosystems to climate variations.[6]

The combined effect of all of these factors taken together is an increasingly unpredictable climate for farmers in all corners of the world. Highly variable rainfall and an increased intensity of storms, droughts and floods will create uncertainty for smallholder farmers, who are already very vulnerable to environmental changes. To make matters worse, shifting habitat conditions for agricultural pests and disease pathogens will leave farms vulnerable to outbreak, and warmer air temperatures are expected to accelerate the breakdown of soil organic matter, affecting fertility and soil-water retention.[7]

When yields are uncertain and the environmental health of the land is strained, social stress can form within rural communities. Social stress further increases vulnerability to extreme environmental events such as droughts or floods, so that when the next event inevitably occurs, the effect is even harder felt. Eventually, this cycle of increasing vulnerability can lead to collapse, where rural villages are emptied by migration.[8]

Contemporary developments in global agriculture have tended to increase the vulnerability of farming communities to environmental stresses. The widespread adoption of a single-crop, tillage-based farming model has increased global yields of staple crops since the 1950s, but has also led to the accelerated degradation of soil and water resources. Irrigated agriculture has drained entire water bodies, and heavy dependence on chemical fertilizers has degraded soil health and caused extensive water pollution in only a few decades.[9]

Decreased biodiversity in rural landscapes is a key source of vulnerability for farming communities. Where once farms were populated by complex systems of interrelated plant, animal and insect species, now much of the world's cropland is planted to only four crops.[10] Such heavy reliance on a small set of plant species compromises the resilience of farm systems to environmental changes and greatly increases vulnerability to drought, diseases, and pests.

This grim picture does have a glimpse of a silver lining. Recently, agricultural thinking has shifted somewhat, and the role of smallholder farmers in feeding the world is now increasingly recognized. After years of careless water depletion to supply irrigated agriculture, the emphasis is now on promoting its efficient use. New practices rooted in *agroecology* have shown promise in combining the goals of environmental health and food production, and complex traditional farming systems that incorporate a diverse range of species are increasingly promoted as a more resilient model.[11,12]

Small farmers will be key players in the coming transition toward more sustainable resource use. Traditional crops and land management practices are increasingly valued by scientists and international agencies seeking to rediscover what defines a truly 'productive' landscape. The leaders of the next revolution in agriculture could well be individual farmers who learn, exchange and experiment with old and new farming methods in their own communities.

References

1 Intergovernmental Panel on Climate Change (IPCC), 2014. Climate Change 2014: Synthesis Report. *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri & L.A. Meyer (eds)]. Geneva, Switzerland: IPCC, 151 pp.

2 Ibid.

3 IPCC, 2007. Climate Change 2007: Synthesis Report. *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri & A. Reisinger (eds)]. Geneva, Switzerland: IPCC, 104 pp.

4 Ibid.

5 Ibid.

6 World Health Organization (WHO) and Secretariat of the Convention on Biological Diversity, 2015. *Connecting Global Priorities: Biodiversity and Human Health*. Geneva, Switzerland: WHO, 275 pp.

7 Alteri, M.A. and Koohafkan, P., 2008. *Enduring Farms: Climate Change, Smallholders and Traditional Farming Communities*. Penang, Malaysia: Third World Network, 58pp.

8 Rockström, J., 2003. Resilience building and water demand management for drought mitigation. *Physics and Chemistry of the Earth, Parts A/B/C*, 28, pp. 869–877.

9 Ongley, E.D., 1996. *Control of Water Pollution from Agriculture*. Rome: Food and Agriculture Organization of the United Nations (FAO).

10 David Tilman, 1999. Global environmental impacts of agricultural expansion: the need for sustainable and efficient practices. *Proceedings of the National Academy of Sciences of the United States of America*, 96(11), pp. 5995–6000.

11 Altieri, M.A., 1999. Applying agroecology to enhance the productivity of peasant farming systems in Latin America. *Environment*, 1(3/4), pp. 197–217.

12 Alteri, M.A. and Koohafkan, P., 2008. *Enduring Farms: Climate Change, Smallholders and Traditional Farming Communities*. Penang, Malaysia: Third World Network, 58pp.

Part 2 Improving Water Productivity in Rainfed Agriculture

Preamble to Part 2

Although agricultural literature devotes much of its attention to irrigation methods and equipment, the vast majority of farms across the world, and especially across the tropics, are exclusively rainfed. Globally, rainfed agriculture represents 80% of all cultivated farmland, on which 60% of the world's food crops are grown.[1] In sub-Saharan Africa over 95% of all farmland is purely rainfed, and a full 90% of all crops are produced in this way. Rainfed farming also dominates in Latin America (90% of farmed land), South Asia (60%), East Asia (65%) and the Middle East and North Africa (MENA) countries (75%).[2] Most of the world's grain crops are purely rainfed.[3]

These statistics, however, reflect a misconception that there is a clear dividing line between 'rainfed' and 'irrigated' agriculture projects. In fact, the distinction is rarely so cut and dry. As introduced in Chapter 1, farming includes a continuum of water management practices spanning from purely rainfed to purely irrigated agriculture, and most projects lie somewhere between these two extremes. Just as many rainfed projects incorporate some degree of irrigation in order to mitigate dry spells, irrigated agriculture projects should also strive to make the best use of available rainfall in order to minimize blue water withdrawals.

Part 2 will discuss strategies for improving the water productivity of rainfall in agriculture, also known as *rainwater productivity*. This value measures the efficiency of rainwater infiltration and storage in the soil, and the capacity of crops and cropping systems to encourage the productive use of that water.

At its most basic level, rainwater productivity refers to the amount of crop produced with a given amount of rainfall. This is a slight variation on the water productivity formula:

Equation P2.1

$$\text{Rainwater productivity} = \frac{\text{Yield (kg or \$)}}{\text{Seasonal rainfall (mm/season)}}$$

Enhancing rainwater productivity boosts the farm's ability to withstand dry spells and produce good harvests even with limited water supplies. Because water withdrawals and irrigation equipment usually represent a high cost for the farmer, investments in rainwater productivity can provide a better cost–benefit ratio (investment efficiency, Chapter 1) than investments in irrigation infrastructure. While the terminology used in Part 2 often refers to purely rainfed farming systems, these techniques apply to both rainfed and irrigated agriculture projects. Maximizing rainwater productivity will also help improve the efficiency of irrigation practices because they improve the soil's ability to capture and keep the water applied.

Situation of Rainfed Farming Systems Throughout the World

Across the globe, crop yields obtained from rainfed agriculture projects are considerably lower than those of irrigated agriculture. Data on worldwide cereal yields from 1995 show that in that year, yields from rainfed farms in developing countries averaged 1.5, t/ha, compared with an average of 3.25 t/ha on irrigated lands.[4] In sub-Saharan Africa, average rainfed cereal crop production was just over one-tenth that of irrigated cereals in the USA.[5]

Ingrained in these bleak statistics is optimism about the potential for yield increases in rainfed agriculture. While irrigated lands have largely already reached their maximum potential, rainfed agriculture holds much promise for improvement. The large disparity among (predominantly rainfed) grain yields from different parts of the world is a testament to this potential. See Fig. P2.1 for a comparison of average grain yields from different world regions in 2013.

It is of course more relevant to compare actual rainfed crop production with *potential yield*, which refers to production levels that would theoretically be possible under ideal management, given local climate conditions. In most cases yields produced on rainfed farms (evaluated at 0.1–1.5 t/ha) are between one-tenth and one-half of their potential yield (3–5 t/ha).[6] The estimated *yield gap* between actual and potential yields in rainfed grains in selected countries is illustrated in Fig. P2.2.

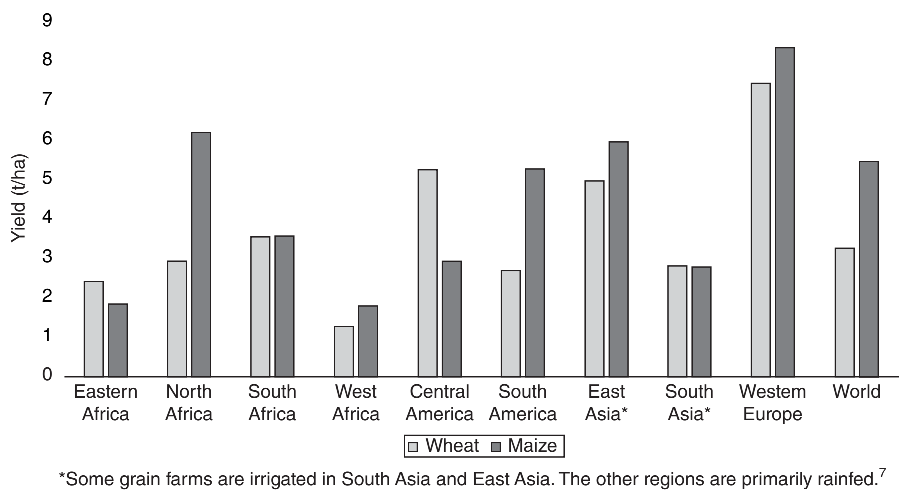

Fig. P2.1. Comparison of average yields for major grain crops (wheat and maize) in different world regions (data: FAOSTAT, 2013).[8]

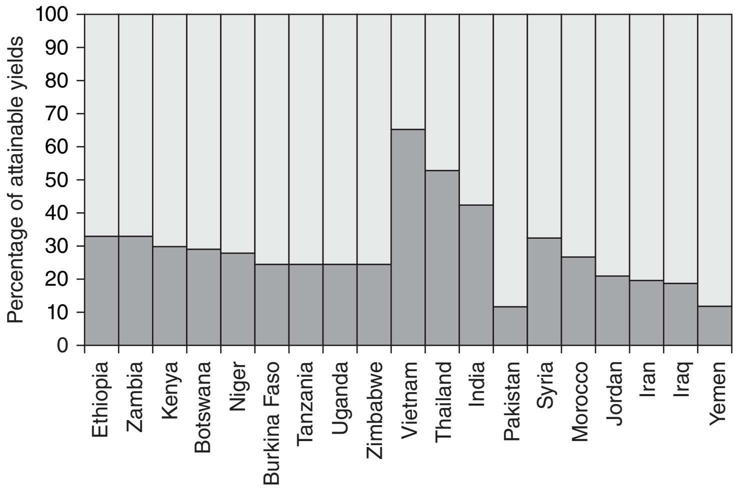

Fig. P2.2. Actual and potential yields for major grains in rainfed agriculture for selected countries (Source: Rockstrom *et al*., 2010).[9]

Global agricultural production has increased dramatically over the past five decades as the result of a worldwide push toward intensification in farming. The scale of yield improvements achieved since the middle of the 20th century is impressive, amounting to more than a doubling of global food crop production.[10] However, recently the pace of change has slowed, and rampant land degradation threatens to reverse early gains in productivity.[11,12] Research suggests that the significant increase in yields made possible during the 'green revolution' that transformed agriculture in the 1960s, 1970s and 1980s was primarily attributable to the expansion of agricultural land area and investments in mechanized, irrigated agriculture, and that the potential of these approaches has largely been exhausted.[13] Modern yield increases will need to come from improved productivity on smallholder farms without formal irrigation infrastructure, which make up the vast majority of agricultural projects on earth.

The potential for yield improvement in rainfed agriculture remains high. Recent studies suggest that poor rainwater partitioning, and not absolute lack of water, is largely responsible for low yields on farms in semi-arid climates.[14] This implies that considerable yield improvements are possible when management practices are changed to improve the infiltration and retention of rainwater and runoff. Yields in rainfed areas can be as little as one-tenth of their potential, and it has been proposed that yields could feasibly be doubled with only small improvements in the proportion of rainwater that is effectively stored in the soil.[15] This potential holds true even on small, resource-poor farms threatened by climate instability.[16]

Enhancing Rainwater Productivity in Smallholder Agriculture

Enhancing productivity on smallholder farms in water-scarce areas with limited financial resources represents a particularly complex challenge. These farms will need to produce 'more crop per drop' while taking care to support the health of a water-stressed natural environment.

Part 2 introduces a range of management practices that have shown promise in improving the productivity of rainwater on smallholder farms. Fundamentally, the goals of the various practices described in the following chapters are:

1. Getting more water.
2. Keeping more water.
3. Using available water wisely.

In order to conceptualize the various practices that will be introduced in Part 2, it can be useful to visualize the soil layers surrounding the crop root zone as a huge water storage reservoir (Fig. P2.3).

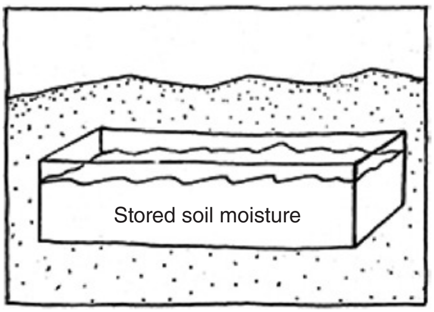

Fig. P2.3. Soil water storage.

With this image in mind, the goals of the soil and water management practices presented are:

1. Increasing the supply of water to the reservoir
   - Direct as much rainwater as possible to the field.
   - Maximize water infiltration into the soil
   - Capture rainwater runoff within the field and encourage its rapid infiltration into the soil.
2. Eliminating leaks from the reservoir
   - Reduce deep percolation by building soil water holding capacity.
   - Reduce water lost through evaporation.
   - Discourage weed (unproductive plant) growth.
3. Using stored water as efficiently as possible
   - Improve the capacity of crop plants to produce a maximum crop yield with minimum water.
   - Plant varieties that will produce good income from within the water resources available.
   - Promote drought-resistant, resilient crop systems.

These goals are summarized in Fig. P2.4.

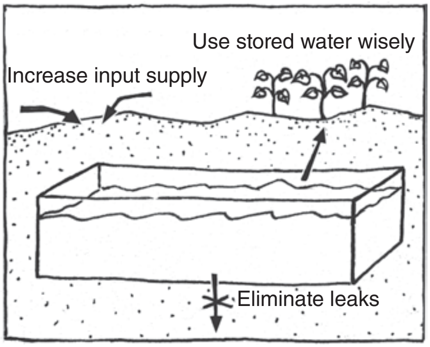

Fig. P2.4. Improving soil water storage and efficient use.

Taking an Integrated Approach

Farming practices that enhance soil water performance are only one part of a wider picture: real improvements in water productivity on rainfed farms will depend on the widespread adoption of holistic land and water management strategies at the farm, district, and watershed scale. Improvements at the farm level will be short-lived if the watershed that it relies on is allowed to degrade. Watershed-scale planning is crucial for water productivity as well as the overall health of agricultural communities. The further reading box below contains some useful resources on this topic.

Even at the individual field scale, an integrated approach is key: research plots have shown that water productivity improvements are maximized when soil and water conservation practices are combined with improvements in fertilization, sustainable land management, integrated pest management, and the adoption of improved crop varieties.[17] The practices described in Part 2 should be considered to be individual components of a larger strategy and not stand-alone options. Individual practices in isolation may only marginally improve water productivity, but an integrated strategy combining soil and water conservation practices with nutrient enhancement and crop management can both provide robust yield benefits and reinforce local environmental health. This combination is crucial to ensuring that yield improvements and farm incomes can be sustained into the future.

Further reading – Integrated watershed management

Integrated Watershed Management in Rainfed Agriculture, book edited by S.P. Wani, J. Rockström and K. Lal, 2012, London: CRC Press (Taylor & Francis).

The New Generation of Watershed Management Programmes and Projects, booklet produced by the Food and Agriculture Organization of the United Nations (FAO). Available at: http://www.fao.org/3/a-a0644e.pdf

Developing an Integrated Water Strategy

Because the interactions among a set of practices can provide additive benefits that exceed the impact of single actions taken alone, an integrated strategy for improving rainwater productivity at the field scale will ideally involve the implementation of a selection of soil, water, nutrient, and crop enhancing practices in combination.

Factors to consider when choosing practices to include in an integrated water management plan include:

1. What are some known water efficiency problems on the farm? The first step should involve studying the farm's water dynamics and identifying potential areas for improvement. Observing the land during a rainfall can be very informative in this respect. For examples, see Table P2.1.

Table P2.1. Observing farm water dynamics.

Observation	Possible efficiency problem
Most rainwater runs off the field during heavy rains	• Poor infiltration • Too much field slope
Water pools on the field during and following rain events	• Poor infiltration • High evaporation loss
Soil dries out quickly between rains	Poor soil water holding capacity
Plants show consistent signs of water stress	Crop variety is not well-suited to available soil water conditions
Etc.	

2. Which practices are already in use within the farmer's peer circles? It is much easier to embark on new methods when other farmers working nearby are also interested or have experience in this area.
3. What degree of investment is available and what is the potential cost–benefit ratio (investment efficiency) of the selected practices? Strategies should be developed to provide a maximum benefit at minimum cost. Recall that 'cost' includes the labor required to implement and maintain the chosen strategy.

The appropriateness of each practice for a particular farm will depend on specific local conditions of soil profile, cropping system, landscape, and rainfall distribution. Actions that improve rainwater productivity on one farm may have no impact on the next. In this regard it is useful to adopt a trial-and-error approach based on careful soil and crop monitoring. This type of approach can be time-consuming for the farmer, but eventual payoffs are high. An effective integrated water strategy should be responsive to ongoing changes observed on site, and continually evolve to reflect recent results and changing climate conditions.

Topics Covered in Part 2

The chapters in Part 2 introduce the most common soil and water management practices used to get more water to the field, keep it there, and use it wisely.

This includes practices designed to improve soil water holding capacity/reduce water losses (Chapter 6) and increase the amount of water supplied to the field through rainwater harvesting (Chapter 7). Part 2 also includes a primer on how crop choices and cropping systems can help foster drought resilience (Chapter 8). The final chapter offers an introduction to conservation agriculture, a set of soil and water management practices that has shown good potential for improving crop yields while promoting soil health in some water-scarce regions (Chapter 9).

It is worth noting that several of the practices outlined in these chapters are presented as distinct concepts only for the sake of clarity. In reality, many soil and water management practices have overlapping functions, and numerous variations of each concept exist within agricultural practice.

References

[1] Wani, S.P. *et al*., 2009. *Rainfed Agriculture: Unlocking the Potential*. Wallingford, UK: CABI, p. 36. Based on data from FAOSTAT 2005 (Food and Agriculture Organization of the United Nations (FAO), 2005).

[2] Ibid. p. 1.

[3] Rosegrant, M.W. *et al*., 2002. *The Role of Rainfed Agriculture in the Future of Global Food Production*. Washington, DC: International Food Policy Research Institute, pp. 57–58.

[4] Ibid.

[5] Ibid.

[6] Rockström, J., 2003. Resilience building and water demand management for drought mitigation. *Physics and Chemistry of the Earth, Parts A/B/C*, 28, p. 875.

[7] Created using data from FAOSTAT, 2013. Database. Rome: FAO. Available at: http://faostat3.fao.org/home/E [Accessed June 10, 2016].

[8] Ibid.

[9] Reproduced with permission from Rockström, J. *et al*., 2010. Managing water in rainfed agriculture – the need for a paradigm shift. *Agricultural Water Management*, 97(4), p. 545.

[10] FAO, 2011. *Save and Grow – a Policymaker's Guide to the Sustainable Intensification of Smallholder Crop Production*. Rome: FAO, p. 4.

[11] FAO, 2011. *The State of the World's Land and Water Resources for Food and Agriculture (SOLAW) – Managing Systems at Risk*. London: Earthscan, p. 108.

[12] Sayre, K. & Govaerts, B., 2011. Use of conservation agriculture to improve farming systems in developing countries, in P. Tow *et al*., eds, *Rainfed Farming Systems*. Dordrecht, The Netherlands: Springer, p. 862.

[13] FAO, 2011. *Save and Grow – a Policymaker's Guide to the Sustainable Intensification of Smallholder Crop Production*. Rome: FAO, pp. 5–10.

[14] Rockström, J. & Falkenmark, M. (2000). Semiarid crop production from a hydrological perspective: gap between potential and actual yields. *Critical Reviews in Plant Sciences*, 19(4), p. 1.

[15] Ibid.

[16] Ibid.

[17] Wani, S.P. *et al*., 2009. *Rainfed Agriculture: Unlocking the Potential*. Wallingford, UK: CABI, pp. 11–17.

6 Soil-focused Strategies: Reducing Water Loss

Chapter 2 introduced the concepts of productive and unproductive water uses within the overall farm water budget. Recall that the only fully productive use of water is crop transpiration (T), which is supplied by readily available soil water stored within the root zone. Typically, the percentage of rainfall that ultimately translates into transpiration is very low, in most cases between 15% and 30%.[1] Unproductive water uses, including evaporation, runoff, weed growth and deep percolation result in the loss of the remaining portion of the water budget. Loss percentages vary widely by context – in extreme cases, the combined forces of evaporation, runoff and deep percolation can consume more than 90% of the rainwater falling on the field.[2]

In order to improve rainwater productivity, farm management practices must seek to shift the way that water inputs from rain are partitioned among these competing uses. The goal is to promote infiltration and reduce water losses as much as possible, leaving more water available for use in crop transpiration.

The root causes of water loss, especially deep percolation, evaporation and runoff, are closely interrelated. These can be tackled together with management practices that enhance soil water holding capacity, improve infiltration, and cover and protect the soil. This category of practices, sometimes collectively termed *soil and water conservation*, also provides added benefits by protecting the soil against erosion and other forms of land degradation.

The soil and water conservation practices outlined in this chapter are not an exhaustive list of possible techniques, but do represent most major types of intervention that have been successful on small farms across the tropics. Most of the practices presented perform multiple functions by reducing water loss while also providing generalized benefits in terms of soil health and overall farm resilience.

Improving Water Holding Capacity

Water loss to deep percolation is difficult to evaluate because the conditions that influence it exist deep in the soil. Farmers are also faced with the dual challenge of promoting the effective infiltration of water into the first layers of soil, while simultaneously discouraging its further downward movement away from the root zone. The best strategy for keeping water in place is the enhancement of water holding capacity in the soil layers surrounding the root zone.

As discussed in Chapter 3, soil water holding capacity is especially dependent on:

- Soil particle size – Fine particles (e.g. clay or silt) increase the surface area where water can 'attach' to the soil, helping it resist against gravity's pull and keeping the water in place.
- Organic matter content – Organic matter serves to increase the aggregation (clumping) of soil particles and provides pores for water retention and movement. Box 6.1 explains the importance of the organic matter content of the soil.
- Compaction – Soils that are compacted around the root zone will retain much less water than loose, uncompacted soils.

This section introduces a range of practices that contribute to the improvement of soil water holding capacity: these include *cover cropping, fallow, residue recycling, agroforestry* and *conservation agriculture*.

Box 6.1. The importance of organic matter content

Enhancing organic matter content is a key priority for improving water holding capacity and maintaining healthy soil. Organic matter serves several roles within the soil structure: (i) it supplies aggregate materials to aid in moisture retention; (ii) it provides nutrients for use by plants; and (iii) it creates habitat and food for soil organisms that help build soil structure and porosity. Farm soils typically contain less than 10% organic matter by weight, but this small portion is crucially important.[3] Soils in dryland areas, and those that have a long history of agricultural use, tend to be very low in organic matter. The loss of organic matter is both a cause and a symptom of most forms of land degradation.

Organic matter is formed when plant and animal residues decompose in or on the ground. Common sources in agriculture include leaf litter, crop residues, root tissues, animal dung, fungi, and dead soil organisms. As these residues slowly decompose in the soil, they release nutrients and other key elements back into the earth. The physical remnants of decaying materials add heterogeneity to the soil and create pore spaces that encourage the free movement of air, water, and plant roots. They also attract beneficial microorganisms that keep the soil healthy and alive.

The maintenance of a healthy and biologically rich soil environment depends on an interconnected set of natural cycles that circulate carbon, nutrients and water through the soil–plant system (Fig. 6.1). Organic matter is the transport medium for this cycling: water and nutrients are taken up from the soil during plant growth, then returned to the ground as plant residues or manures to form soil organic matter. As this organic matter is gradually broken down by soil microorganisms, its stores of carbon, nutrients and water become available for reuse by new plants. The process also generates humus, a stable soil-building by-product that binds nutrients in long-term storage for later use. In undisturbed natural

Continued

Box 6.1. Continued.

environments, these cycles of growth and decay continue uninterrupted and provide a favorable environment for plant growth.

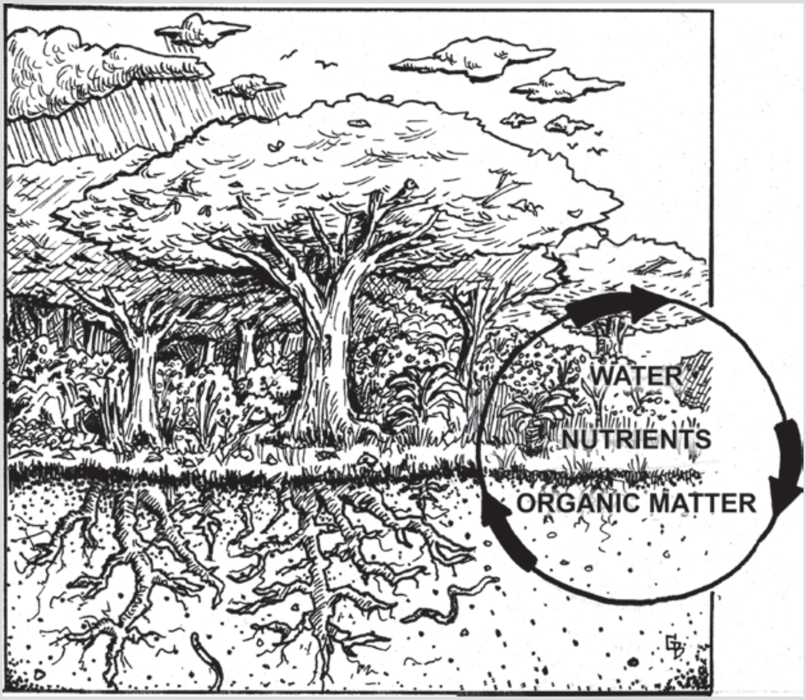

Fig. 6.1. Cycling of water, nutrients and organic matter through the plant–soil system.

Most types of modern ‘conventional’ farming fail to retain soil organic matter because plant residues are removed, burned, or fed to livestock instead of returned to the soil. Soil disturbance by plowing is also detrimental to organic matter content because it hastens the breakdown of decaying matter by exposing it to air and sunlight. Farming practices that negatively affect the soil’s organic matter content include:[4]

- tillage;
- overgrazing;
- monoculture;
- burning of natural vegetation or crop residues;
- removal of crop residues from the field;
- chemical fertilizer application; and
- bare fallow.

The loss of organic matter causes soil to leach nutrients and become thin, crusted, and dry. To maintain fertile soils that hold moisture well, the regeneration of soil organic matter must be promoted in parallel with crop production. Some farming practices that promote soil regeneration on agricultural lands are described in the following pages.

Further reading – Organic matter content

The Importance of Soil Organic Matter: Key to Drought-resistant Soil and Sustained Food Production, booklet produced by the Food and Agriculture Organization of the United Nations (FAO). Available at: www.fao.org/3/a-a0100e.pdf

Cover cropping and green manures

Cover crops are low, dense crops used as a ground cover and nutrient source to support the success of primary crops. They can be grown as a secondary crop during the growing season, or cultivated during fallow to regenerate and protect the soil. Once mature, cover crops are often slashed and left on the soil to add organic matter and enhance fertility (at which point they become known as *green manure*). Many cover crops are legumes, chosen for their ability to fix nitrogen. Leguminous cover crops and green manures are soil amendments that provide a cheap and natural alternative to chemical fertilizer. Beyond soil building, cover cropping has a range of additional benefits: (i) it reduces evaporation from the soil surface; (ii) it promotes water infiltration into the top layers of soil; (iii) it provides habitat for beneficial organisms; and (iv) it discourages both weeds and erosion.

There are several types of cover crops:

- A ‘winter’ cover crop is sown at the end of the primary crop’s growing season, and cultivated during the ‘winter’, or fallow period.
- A ‘break’ cover crop is cultivated when there is a short pause in the crop rotation.
- ‘Living mulch’ is a cover crop that is grown simultaneously with the primary crop. Its main purpose is to provide soil cover, thereby improving infiltration while reducing evaporation and discouraging weed growth.
- A ‘catch crop’ is planted at the end of the primary crop’s growing season or right after harvest. Catch crops take up residual nutrients in order to prevent them from leaching from the soil profile.
- Forage cover crops are useful both as soil cover and as forage for animals.

Cover crops are chosen according to their complementarity with the primary crop, either as an intercrop or as part of a rotation. Key features to consider when evaluating crop complementarity include rooting depth, water requirement, time to maturity, and nutrient-fixing capacity. Cover crops should also be chosen for their ability to grow well (cover the soil) in local conditions, and the seeds should be easy to buy and sell on the local market. Ideally, more than one cover crop would be planted at once, in order to limit vulnerability to pests and disease.[5]

Cover crops may also be harvested and sold to add to farm income. If cover crops will be harvested, it is important to consider how much work will be required for land preparation, maintenance, weeding and harvest of this second crop. In general, species with large grains or pods (e.g. pigeon pea and mucuna species) require less labor than small-pod varieties (e.g. vetches and grasses).[6]

On degraded soils, the cultivation of grasses and cereals as cover crops will help to break up deep soil layers and provide thick, slowly decaying crop residues to leave on the surface of the soil. After soil structure has improved, leguminous crops can be used to provide nutrient enhancement.[7] Leguminous cover crop residues decompose more rapidly than grass residues, so a mix of the two types makes a very effective mulch.[8]

The main disadvantage of cover crops is that they can compete with primary crops for limited water and soil nutrients. On rainfed farms in areas with less than 500 mm annual rainfall, available soil water will most likely be insufficient to support both a cover crop and the primary crop during the growing season.[9] When competition for soil water and nutrients is a concern, shallow-rooted cover crops can be paired with deep-rooted crops to minimize conflict. Seeding should be timed to avoid any overlap between the high-water-demand growth stages of the primary and cover crop.

Green manure is the term used to describe the practice of cultivating leguminous cover crops until just after their flowering stage, then turning them back into the soil while still green (these can also be grown longer for seed, and then cut). There are multiple benefits to green manure application: the incorporation of legume crops into the soil provides added water and nutrients, enhances microbial activity, and boosts soil organic matter. Green manures shouldn't be turned into the soil with conventional plows because their residues can get lost in deep soil layers where they will decompose without benefitting the primary crop.[10] Plowing also requires disturbing the soil, which is counterproductive to building soil organic matter. Slashing green manure crops and leaving them to decompose on the surface, or turning them only slightly to sit just under the top soil layer, is considered a more effective way to gradually recycle the nutrients and water of cover crop residues while simultaneously encouraging the activity of soil organisms. The timing of operations is important for optimizing the reuse of nutrients from cover crops and green manures. See the further reading box below for more information on using these techniques successfully. Table 6.1 lists some species of legume that are commonly used as cover crops and green manures.

Table 6.1. Common leguminous cover crops and green manures.[11]

Common name	Scientific name
Azolla	*Azolla pinnata*
Bambara groundnut/jugo bean	*Voandazeia subterranea*
Buckwheat	*Fagopyrum esculentum*
Butterfly pea	*Clitoria ternatea*
Calliandra	*Calliandra* spp.
Calopogonium	*Calopogonium mucunoides*
Centrosema	*Centrosema pubescens*
Choreque	*Lathyrus nigrivalvis*
Common pea (pea)	*Pisum sativa*
Cowpea	*Vigna unguiculata*
Crotalaria	*Crotalaria* spp.
Desmodium	*Desmodium ovalifolium*

Continued

Table 6.1. Continued.

Common name	Scientific name
Faidherbia	*Faidherbia albida*, formerly *Acacia albida*
Fava bean/broadbean	*Vicia faba*
Grasspea	*Lathyrus sativa*
Groundnut (peanut)	*Archis hypogea*
Indigophera	*Indigophera* spp.
Jackbean	*Canavalia ensiformis*
Lablab bean/black bean/ horsepea/hyacinth bean	*Dolichos lablab*
Leucaena	*Leucaena leucocaphala*/*L. diversifolia*
Lima bean	*Phaseolus lunatus*
Lupines	*Lupinus albus*, *L. luteus* and *L. angustilofolius*
Mother of cacao	*Gliricidia sepium*
Mucuna/velvet bean	*Mucuna* spp.
Mung bean/green gram	*Vigna radiata*
Nyama	*Piliostigma reticulatum*
Perennial peanut	*Arachis pintoi*
Pigeon pea	*Cajanus cajan*
Rice bean	*Vigna umbellata*
Runner bean	*Phaseolus coccineus*
Sesbania	*Sesbania rostrata*
Soybean	*Glycine max*
Spineless mimosa	*Mimosa* spp.
Stylo	*Stylosanthes* spp.
Sunnhemp	*Crotalaria ochroleuca*
Sweet clover	*Meliuotus albus*
Swordbean	*Canavalia gladiatus*
Tarwi	*Lupinus mutabilis*
Tephrosia	*Tephrosia vogelii*
Tropical kudzu	*Pueraria phasioloides*
Vetch	*Vicia toluca*
Wild sunflower	*Tithonia diversifolia*
Yam bean	*Pachyrhizus erosus*

Further reading – Cover crops

Green Manures/Cover Crops, booklet produced by the Henry Doubleday Research Association (HDRA). Available at: www.gardenorganic.org.uk/sites/www.gardenorganic.org.uk/files/resources/international/GreenMan.pdf

Restoring the Soil: A Guide for Using Green Manure/Cover Crops to Improve the Food Security of Smallholder Agriculture, booklet by Bunch, R., 2012, produced by the Canadian Foodgrains Bank, Winnipeg, Canada.

Soil cover, Chapter 5 in the book *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa* by the African Conservation Tillage Network (ACT) & the International Institute of Rural Reconstruction (IIRR), 2005. Available at: www.fao.org/ag/ca/AfricaTrainingManualCD/PDF%20Files/05SOIL1.PDF

Fallowing and stubble

Fallow periods allow soils to regenerate critical nutrients after a period of crop cultivation. Fallowing is a traditional practice that has been in use since the early days of agriculture. In recent decades, as farmers sought to intensify production with the help of mineral fertilizer inputs, the practice of fallowing declined significantly. This is a dangerous trend, as fallow periods are key to soil regeneration. The reduction of fallow in industrialized agriculture is a leading cause of land degradation.

Leaving crop stubble on the field during fallow can further enhance soil regeneration during rest periods. Stubble provides an added source of organic matter for sustaining soil organisms, and its presence at the soil surface decreases erosion while simultaneously promoting the infiltration of off-season rains. If livestock routinely feed on stubble during fallow, fields may need to be fenced to provide this benefit. Burning stubble should be avoided, as this practice strips the soil of much-needed moisture and nutrients.[12]

The use of cover crops during fallow is popular with organic farmers because the rate of soil nitrogen regeneration is more rapid with the use of legume cover crops than with bare fallow. The added expense of an off-season cover crop makes this practice less widespread among resource-poor farmers. Cultivation of off-season, marketable legume crops can improve the cost–benefit scenario of cover cropping during fallow.

Crop residue recycling

To the extent possible, crop residues should be reintegrated into the soil profile so that their nutrients, water, and carbon stores can be recycled. Decomposing residues enhance soil structure, add organic matter, and boost the activity of soil organisms (see Box 6.1 for the importance of organic matter).

In the first years after converting to residue recycling, it can be difficult to find a large volume and variety of plant residues on the farm itself. To speed the process along, additional residues can be sourced from off the farm: sometimes neighbors or other farmers in the same district will have residues to spare. Some farmers choose to devote a part of the field to producing plants specifically for use as residues. Eventually, the production of crops and residues should become self-sustaining.

Residues can be reused through *manure application*, *composting*, or *mulching*. These are also nutrient management strategies: they ensure that valuable micro- and macro-nutrients are returned to the farm system after each harvest. In modern commercial agriculture, where successive cycles of intensive crop cultivation have replaced traditional methods of fallowing fields and allowing them to regenerate, nutrient mining (where plant nutrients are repeatedly withdrawn without renewal) is a major concern. Chemical fertilizers are commonly used to replace lost soil nutrients, but these additives are short-term fixes that do little to encourage soil health.

Manure application

Many farmers trust manure application as their principal fertilization strategy. Manure is an excellent source of nutrients, especially organic carbon, which is often a limiting factor in farm soils.[13] Manure use has declined in many parts of the world in recent years as chemical fertilizer use has become more widespread. Some farmers also use manure for other purposes such as fuel or construction, thereby diverting it from the soil regeneration cycle. Especially in cases where livestock are given farm residues to eat, animal manure should be returned to the soil as much as possible. Manure is also a potential source of water contamination, so it should be stored in a sheltered, protected location where it can't run off toward water bodies or drinking water wells during rain events. When spreading manure on the field, direct contact with plant tissues is to be avoided.

Composting

Composting is the controlled decomposition of plant residues, kitchen wastes and animal dung to produce a stabilized, soil-like material that can easily be reused in agriculture. Finished compost is easier and safer to handle than manure, and is an excellent natural source of easily accessible plant nutrients. Like manure, it also provides organic matter and improves the structure of the soil. The integration of compost into farm soils can reinvigorate degraded soils when performed as a regular practice each growing season. Finished compost can be spread in a thin layer over the field surface or turned into the top layers of soil. When composted material is in limited supply, it can be used directly in planting holes or mixed in with the soil used to produce seedlings.

In recent years, composting has emerged as a successful farmer innovation in the drylands of Eastern Africa, where degraded soils have seen a marked improvement in fertility following compost application.[14] Box 6.2 describes two simple methods for making compost.

Box 6.2. How-to: compost

The simplest method for making compost is the compost heap. (Fig. 6.2). In warm climates, compost heaps should be built up in a shaded, protected area. In termite-prone regions, a base layer of ash spread onto the ground before building the heap will help prevent infestation. Next, slowly decomposing materials such as woody sticks or maize stalks are laid in a bottom layer about 30 cm thick – these will provide aeration and drainage. From there, alternating layers of fresh crop residues, dried plant residues, food waste, animal manure and ash are added until the pile is about 2 m high. The layers of dry residue are critical to maintain air infiltration and prevent rotting – dry vegetative matter such as leaves, grass or crop residues that have been allowed to dry in the sun should be added at least every third layer. When the pile is complete, it can be covered with a layer of topsoil or dry matter to retain humidity. In areas with low rainfall, the pile will need to be wetted from time to time so that it stays moist, but not wet. The pile can also be built in a hole to preserve moisture.

Continued

Box 6.2. Continued.

After 3 weeks, the completed heap should be turned to expose the inner layers to the air. A long stick can be inserted into the centre of the pile in order to test its temperature: the pile should get very hot if the compost is proceeding successfully. Using this formula, the compost should be ready to use on the field within 45–60 days.

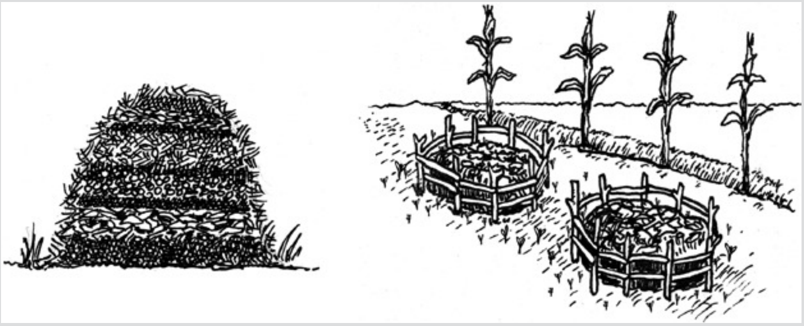

Fig. 6.2. Compost heap (left) and compost baskets (right).[15]

Another practice gaining in popularity is the compost basket (Fig. 6.2). In this method, a series of crude basket structures are created in the field by driving twigs or thick grass about 15 cm into the ground near the base of the crop. Compostable materials are then added to the 'basket' in the same way described above. Baskets should be spaced at least 1 m apart and at least 1 m from the base of the crop plants. Compost baskets are often installed in kitchen gardens or near fruit trees. The benefit of this method is that the compost can be used in real time by the growing crops. It can also be less labor intensive to maintain than the heap method. However, baskets cause obstructions in the field that the farmer will have to work around.[16]

Further reading – Composting

Composting in the Tropics I and *II*, booklets produced by HDRA. Available at: www.answers.practicalaction.org/our-resources/item/composting-in-the-tropics

Mulching

Mulching simply involves covering bare surfaces between and among crop rows with a layer of organic material, so that the surface of the soil is protected from the rain and sun (Fig. 6.3). Covering bare earth with mulch protects the soil environment, discourages weeds, and reduces erosion by wind and water. It is also very effective at reducing runoff and evaporation. Mulching with crop residues is a simple, economical practice that provides significant benefit yet requires little labor. As with stubble, farms with livestock may have to fence the field if raw crop residues are used as mulch. The residues of weed plants that have passed the flowering stage, or of parasitic plants such as *Striga* spp., should not be used as mulch.[17]

Fig. 6.3. Bare (left) and mulched (right) crop rows.

Agroforestry

Agroforestry is the practice of growing crops alongside trees and shrubs. Agroforestry practices are beneficial for soil health in a variety of ways: perennial trees and shrubs provide a steady source of organic matter useful for soil building, and their deep, woody roots encourage water infiltration and stabilize the soil against erosion. The roots of trees and bushes are able to access parts of the soil profile that crops cannot, so their fallen leaf litter and dead branches can recycle nutrients and water from deep soil layers to benefit crop plants. The roots of woody perennial plants also support a range of soil organisms that keep the soil healthy even during the dry season.[18] The residues of woody plants are the keystone of agroforestry: these are re-integrated directly into the soil or turned into compost. A variety of tree and shrub species of varying heights should be included in an agroforestry system: these can be chosen according to their capacity to produce food, fodder and/or fuel for sale or reuse on the farm. Agroforestry promotes healthy and resilient plants that require few inputs because they are nourished by the continuous cycling of nutrients, water and organic matter through the farm ecosystem.

Alley cropping, also known as alley farming and hedgerow intercropping, is a popular form of agroforestry practiced in the humid and sub-humid tropics. In this system, crop plants are interspersed by rows of low trees or shrubs, usually of the legume family.[19] These 'hedgerows' of woody leguminous plants nourish the soil through nitrogen fixing and the decomposition of plant residues. The use of a hedgerow crop pattern provides the benefits of agroforestry systems while maintaining the ease of maintenance of a row crop. The tree and shrub species used in alley cropping must be continually pruned so that they do not shade or crowd out the primary crop.

Further reading – Agroforestry

Agroforestry in the Tropics, a booklet published by HDRA in 2001.

An Introduction to Agroforestry, a booklet by P.K. Ramachandran Nair. Available at: www.worldagroforestry.org/Units/Library/Books/PDFs/32_An_introduction_to_agroforestry.pdf

Conservation agriculture (conservation tillage, no-till farming)

For decades, conventional agricultural literature has encouraged the regular tillage of the top layers of farm soil to prepare for planting and remove weeds. However, it is now widely recognized that tillage damages the soil structure, wastes organic matter, causes compaction, and exposes soil to erosion. Tillage also disrupts the habitat of soil organisms whose activity is crucial to keeping the earth alive and healthy.

Conservation agriculture is the term used to designate a set of farming practices that involve minimal or no tillage. The practices outlined in this chapter are all close relatives of conservation agriculture, but the techniques of conservation agriculture are normally adopted together, through a conversion process involving the whole farm system. Conservation agriculture is discussed in detail in Chapter 9.

Controlling Evaporation

Evaporative water loss from the top layers of soil can represent a considerable fraction of water use, especially on farms where bare soil is left exposed between crop rows. In these cases, evaporation can consume up to 50% of rainfall water inputs.[20] This is much higher than the proportion that becomes useful as plant transpiration. Evaporation is highest when the density of the plant canopy is low, as this leaves more soil surface exposed to direct heat from the sun's rays.

Evaporation happens under both sunny and cloudy conditions, and can in fact be more significant in moderate heat than on a sunny hot day. In hot and dry conditions, the top layer of soil dries out quickly then acts as hydraulic barrier protecting the lower layers from evaporative water loss, but in moderate heat or humid conditions this does not occur.[21]

Efforts to reduce evaporation provide the most significant benefit during early growth stages, when plants have small leaf surface area and are particularly sensitive to water stress. Early preventative action is also useful because evaporation is a self-reinforcing phenomenon: the more water is lost to evaporation, the more crop growth will be stunted, which in turn reduces the shading of soil provided by leaf canopy, leaving it exposed to further evaporation.

In irrigated agriculture, the timing of water applications is critical in reducing evaporation because it influences the length of time that water spends pooled up on the surface of the soil. Similarly, the amount of rainwater inputs lost as evaporation will be more significant following heavy rains, which tend to be slow to infiltrate. Water evaporates more rapidly from free water surfaces than from soil, so pooling should be avoided whenever possible. In both rainfed and irrigated agriculture, furrows and drainage channels should be designed to maintain steady transfer rates and discourage standing water. To the extent possible, open-water channels and water storage structures should be covered to minimize evaporation loss. When designing storage structures, deep shapes will be less susceptible to evaporation than large, flat shapes because the area of free water surface is kept to a minimum.

Key strategies for reducing evaporation loss from the field surface involve shading the soil and promoting infiltration. Practices that provide soil shading include: (i) application of mulch cover to bare soil; (ii) use of cover crops during the growing season; and (iii) dense planting and intercropping.

Application of mulch to cover bare soil

Mulching is a very effective way of reducing evaporation loss. The use of dense mulches also has several other benefits, as discussed above. Mulch can be created using any non-toxic organic material, including crop residues or other readily available by-products such as wood chips, straw, or rice husks. Farmers in East Asia and North America have had positive results with the use of plastic mulches to cover planting rows, but this practice can be costly to install.[22] Organic mulch is more cost-effective but will need to be reapplied from time to time as the mulch materials decompose.

Using cover crops during the growing season

Cover crops are useful in reducing evaporation when planted densely in between or among plant rows during the growing season. Of course, cover crops will also use water from shallow soil layers, so cover crops should be chosen based on water available, and according to their potential for providing additional income. Cover crops are not usually an appropriate strategy for reducing evaporation in arid and semi-arid areas because they will compete with the main crop for scarce soil water.

Dense planting and intercropping

Especially when rows are left bare, crop plants should be spaced as densely as is feasible, in order to provide soil shading. Plants that don't produce a wide leaf canopy can be planted in dense pockets, provided that spacing to allow for root spread is respected. This strategy can also discourage weed growth and provide a good microclimate for plants, but could require additional labor if access to crops is made difficult. Dense planting is best achieved through *intercropping*, the simultaneous cultivation of two or more crop types that are known to be compatible. At least one of the chosen species should provide shading for both the soil and the companion plant.

Controlling Weed Growth

Weeds consume soil water that would otherwise be available to support crop development. Weeds should be controlled early so that they do not get a chance to compete with the main crop for water, sunlight or nutrients. One study found that maize yield was reduced by nearly one-half when weeds were allowed to grow for just 15 days in the first month of the season.[23] It is also important to control weeds during fallow periods, because their growth will hinder the soil's ability to regenerate nutrients and store water for later use. Cover crops also need to be weeded.

In conventional agriculture, weeds are commonly removed through tillage, especially during fallow seasons. However, tillage itself can damage soils and deplete soil water. Herbicides are popular with some farmers, but these are expensive inputs, and reliance on only a few herbicide products can lead to resistance in just a few seasons.[24] The problem of weeds remains a constant challenge for the poor farmer: their presence will reduce crop yields but their removal can be expensive, whether in terms of labor (hand-weeding), soil quality (tilling), or money (herbicides). The use of cover crops or dense mulches can provide an interesting alternative for combating weed growth while simultaneously helping the soil. When the availability of mulch materials is limited, it can be preferentially installed around the base of crop plants so that weeds are not allowed to compete directly with crops for soil water. Cover crops should be chosen for their ability to successfully compete with common weeds endemic to the region.

Reducing Runoff

In dryland areas, up to 40% of rainfall is routinely lost as unproductive runoff.[25] Runoff losses are a function of rain intensity, field slope, and soil infiltration rate. Whenever possible, cropping areas should be kept level: a slope of less than 1% is ideal in dry areas. In wet climates, large expanses of flat land can be vulnerable to pooling; in these cases, shallow slopes or drainage gullies are important to prevent waterlogging. See Chapter 11 for more information about soil drainage.

The slope of the field can be determined with a simple measurement if the farmer has access to a spirit level and a long, straight board. The board is placed on the ground lengthwise at a right angle to the slope and propped up on its downhill side until it is level. The slope will be the vertical distance from the top of the board to the ground (on the downhill side) divided by the horizontal length of the board (Fig. 6.4). Slope is usually expressed as a percentage.

Equation 6.1

$$Slope = \frac{Rise\ (distance\ from\ B\ to\ C)}{Run\ (distance\ from\ A\ to\ B)} \times 100\%$$

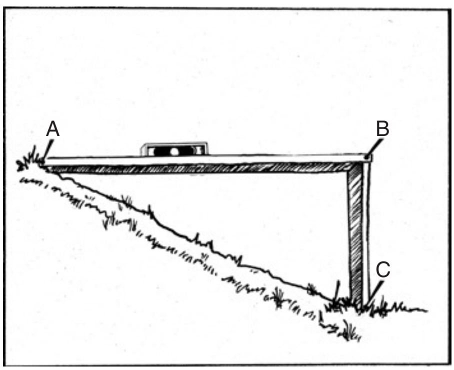

Fig. 6.4. Using a long, straight board and a spirit level to determine the slope of a field

Sloped sites are prone to high runoff losses because rain hitting the ground doesn't have time to infiltrate before being pulled downhill by gravity. Although leveling the entire cultivation area is usually not feasible, farmers with sloping fields can adapt the land levels locally around planted surfaces in order to minimize runoff losses. *Rainwater harvesting* is the general term used to describe land-shaping techniques that are useful for slowing and infiltrating runoff water. The category includes *contour farming* and *terracing*, age-old agricultural techniques used to grow crops in hilly terrain. Rainwater harvesting techniques are described in detail in Chapter 7.

Whether or not rainwater harvesting is practiced, it is beneficial to work to enhance the soil's infiltration capacity as a means to minimize runoff. Infiltration rate is a function of soil texture, surface condition, compaction, and moisture content. Table 6.2 outlines the factors that influence soil infiltration, and provides strategies for improvement.

Soil that is very dry is subject to *surface sealing*, where a crust forms over the top layer of earth. Surface sealing (or *crusting*) is the most significant obstacle to water infiltration in sub-humid and semi-arid zones.[26] Crusting is especially problematic since the process is self-reinforcing: the force of impact of falling raindrops on the dry, crusted soil surface causes it to seal even further. Surface sealing can be prevented by covering and shading bare soil with mulch or by planting cover crops, whose fine roots dig tiny channels in the top layer of soil to prevent sealing.

Table 6.2. Factors that influence soil infiltration and strategies for improvement.[27]

Factor	Good infiltration	Poor infiltration	Strategy for improvement
Soil dryness	Wet (but below field capacity)	Dry	• Enhance soil water holding capacity • Keep soil covered with mulch or plant residues to slow surface drying
Soil topography	Flat, even	Sloped, uneven	• Level the field surface or build terraces on sloped sites
Surface texture Soil cracks	Rough Many	Smooth Few	• Roughen soil surface by hand or plow • Create ridges, basins, or furrows • Cover soil with mulch or plant residues to improve surface texture • Plant cover crops to create infiltration pathways and prevent surface sealing
Soil porosity	High	Low	• Improve soil texture by adding organic matter
Salinity	Low	High	• Adopt salinity management measures

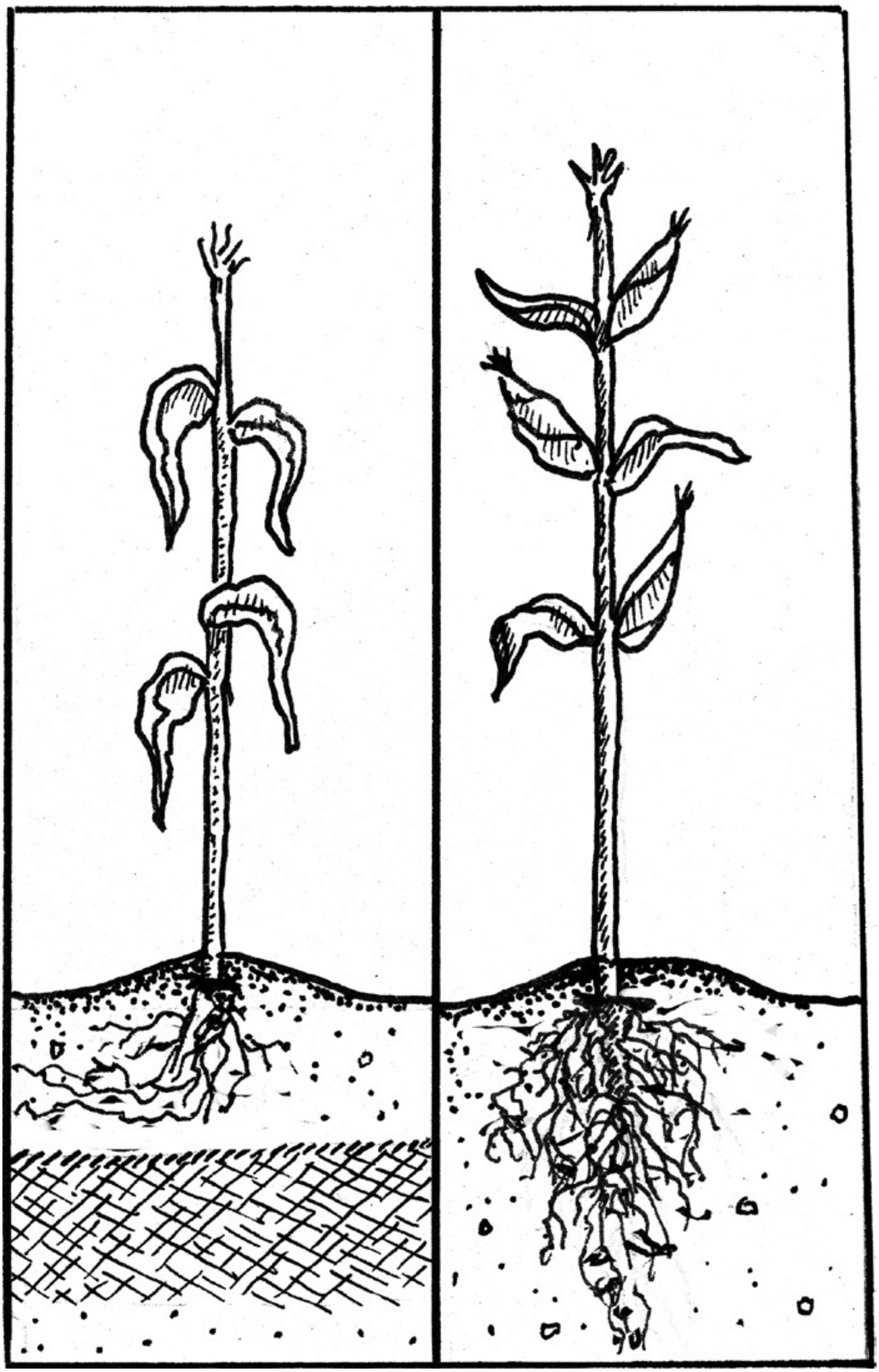

Fig. 6.5. The presence of a soil hardpan (left) decreases infiltration and stunts plant development.

Beyond infiltration into the first layers of soil, it is also important to encourage its downward migration through the subsoil during rain events, in order to avoid the rapid saturation of surface soil layers. Unfortunately, conventional tillage practices tend to impede the downward percolation of soil water beyond a certain depth. Farm soils that have been plowed consistently at the same depth year after year will develop a layer of compacted soil called a *hardpan* (or *plow pan*) directly under the depth of regular tillage. This compacted layer will prevent rainwater from penetrating deep into the soil, leading to increased runoff. Hardpans also stunt the development of plant roots, and plants grown over a hardpan will exhibit signs of stress including rapid wilting, stunted growth, yellowing leaves, and distorted root systems (Fig. 6.5). Hardpans can be broken up through deep tillage below the depth of the pan or by using one of the optimal tillage methods detailed in Chapter 9.

On sloped sites with poor infiltration, runoff can result in the loss of a significant portion of precious rainwater inputs. However, runoff water originating from outside of the immediate crop area can also be viewed as a potential source of additional water to boost the farm water budget. Rainwater harvesting techniques promote the strategic capture of runoff water from within and outside the field for use by crop plants. The next chapter outlines a range of rainwater harvesting techniques.

References

1 Rockström, J. *et al*., 2003. Water productivity in rain-fed agriculture: challenges and opportunities for smallholder farmers in drought-prone tropical agroecosystems, in J.W. Kijne *et al*., eds, *Water Productivity in Agriculture*. Wallingford: CABI, p. 150.

2 Rockström, J., 1997. On-farm agrohydrological analysis of the Sahelian yield crisis: rainfall partitioning, soil nutrients and water use efficiency of pearl millet. Doctoral dissertation. Stockholm: Stockholms universitet.

3 Bot, A. & Benites, J., 2005. *The Importance of Soil Organic Matter*. Rome: Food and Agriculture Organization of the United Nations (FAO), p. ix.

4 Ibid.

5 African Conservation Tillage Network (ACT) & International Institute of Rural Reconstruction (IIRR), 2005. Soil cover, in *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa*. Nairobi: IIRR, p. 94.

6 Ibid. p. 83.

7 Bot, A. & Benites, J., 2005. *The Importance of Soil Organic Matter*. Rome: FAO.

8 ACT & IIRR, 2005. Soil cover, in *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa*. Nairobi: IIRR, p. 89.

9 Anschütz, J. *et al*., 2003. *Water Harvesting and Soil Moisture Retention*, M. Nederlof & J. Anschütz, eds. Wageningen, The Netherlands: Agromisa Foundation, p. 71.

10 ACT & IIRR, 2005. What is conservation agriculture?, in *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa*. Nairobi: IIRR, pp. 1–24, p. 15.

11 Adapted with permission from: (i) Bunch, R., 2012. *Restoring the Soil: a Guide for Using Green Manure/Cover Crops to Improve Food Security for Smallholder Farmers*. Winnipeg, Canada: Canadian Foodgrains Bank; and (ii) ACT & IIRR, 2005. Soil cover, in *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa*. Nairobi: IIRR, p. 84.

[12] O'Leary, G.J. *et al*., 2011. Rainfed farming systems, in P. Tow *et al*., eds, *Rainfed Farming Systems*, Dordrecht, The Netherlands: Springer, p. 110.

[13] Bot, A. & Benites, J., 2005. *The Importance of Soil Organic Matter*. Rome: FAO, p. 48.

[14] Mati, B.M., 2005. *Overview of Water and Soil Nutrient Management under Smallholder Rain-fed Agriculture in East Africa*. Working paper 105. Colombo: International Water Management Institute (IWMI), p. 45.

[15] Adapted from Henry Doubleday Research Association (HDRA), 2001. *Composting in the Tropics*, 2nd edn. Coventry, UK: HDRA.

[16] Box information adapted from Mati, B.M., 2005. *Overview of Water and Soil Nutrient Management under Smallholder Rain-fed Agriculture in East Africa*. Working paper 105. Colombo: IWMI, p. 45.

[17] ACT & IIRR, 2005. Soil cover, in *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa*. Nairobi: IIRR, p. 99.

[18] Bot, A. & Benites, J., 2005. *The Importance of Soil Organic Matter*. Rome: FAO, p. 24.

[19] Mati, B.M., 2005. *Overview of Water and Soil Nutrient Management under Smallholder Rain-fed Agriculture in East Africa*. Colombo: IWMI, p. 49.

[20] Wani, S.P. *et al*., 2009. Rainfed agriculture – past trends and future prospects, in S.P. Wani *et al*., eds, *Rainfed Agriculture: Unlocking the Potential*. Wallingford, UK: CABI, p. 21.

[21] Ali, M.H., 2010. Field water balance, in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, pp. 331–372, p. 351.

[22] Davies, W.J. *et al*., 2011. Novel crop science to improve yield and resource use efficiency in water-limited agriculture. *Journal of Agricultural Science*, 149, p. 124.

[23] Nel, P.C. & Ehlers, J.C., 1987. Die rol van onkruide en die beheer daarvan by mielies. Afrikaans [The role of weeds and their control in maize] Boerdery in Suid-Afrika – Mielies, Department of Agriculture and Water Supply. Republic of South Africa, p. 3.

[24] O'Leary, G.J. *et al*., 2011. Rainfed farming systems, in P. Tow *et al*., eds, *Rainfed Farming Systems*. Dordrecht, The Netherlands: Springer, p. 110.

[25] Bot, A. & Benites, J., 2005. *The Importance of Soil Organic Matter*. Rome: FAO, p. 35.

[26] Morin, J., 1993. Soil crusting and sealing, in *Soil Tillage in Africa Needs and Challenges*. Available at: http://www.fao.org/docrep/t1696e/t1696e00.HTM [Accessed April 18, 2016].

[27] Adapted from Ali, M.H., 2010. Soil: a media for plant growth, in *Fundamentals of Irrigation and On-farm Water Management* Volume 1. New York: Springer, p. 128.

7 Rainwater Harvesting

Unfortunately, it is not feasible for a farmer to decide to 'turn on the rain' to water his fields at the time of his choosing and in the amount needed. To maximize his water supply, he will need to effectively capture all of the rain that falls on the field, and if possible intercept and collect excess rainwater falling on the surrounding area. In purely rainfed farming where no blue water sources are exploited, these are the only available water inputs. Even when surface or groundwater is accessible for use as supplemental irrigation, it is most efficient to first optimize the effectiveness of rainwater before moving water from other sources.

Rain that drains from the field instead of infiltrating becomes *runoff*. Left unchecked, runoff leads to significant water loss, wasting up to 40% of rainwater inputs.[1] Rain runoff is also the principal cause of soil erosion. Rather than allowing runoff to leave the field, landforms such as basins, bunds, and gullies can be used to intercept and direct it toward the base of crop plants where it is needed. The use of land-shaping to capture, direct, and concentrate rainwater is commonly known as *rainwater harvesting* (RWH). Because they discourage the rapid outflow of runoff, rainwater harvesting techniques are also erosion prevention measures.

Farmers in dry climates have been practicing rainwater harvesting for thousands of years. These ancient techniques have seen a recent resurgence in popularity because they are now recognized as a cheaper and more sustainable alternative to irrigation development.[2] Rainwater harvesting is typically practiced on gently sloping cropland and rangeland in the arid or semi-arid tropics, but many of the techniques can be adapted for use in sub-humid climates where dry spells are problematic.[3] Rainwater harvesting can also be useful in facilitating cultivation on difficult and degraded sites because it takes advantage of runoff from crusted, compacted land to supply water to localized pockets of cultivable soil where planting is concentrated. Instead of working the whole field, only those pockets of soil will need to be labored to develop good water holding capacity and fertility.

Rainwater harvesting structures include both a catchment area, where rain runoff is generated, and a cultivated area, where water is accumulated (Fig. 7.1). The ratio of catchment area to cultivated area is the main design parameter of rainwater harvesting structures, and should be determined before construction begins. The catchment area:cultivated area ratio can be estimated based on farmers' experience with the soil, or calculated according to soil type, runoff rate, and plant water requirement. Detailed instructions for calculating the ideal ratio are provided in the pivotal guide *Water Harvesting: A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production* by W. Critchley and K. Siegert, listed in the further reading box at the end of this chapter.

Rainwater harvesting structures are typically installed along a slope in the direction of the *contour line*. The contour is an imaginary line traced across a slope at which all points are at the same elevation. For example, a gully created along the precise contour of a hillside would have no slope, so water added to the gully would not run in one direction or the other. Determining the contour line of the slope is the first step in the construction of most rainwater harvesting structures. It can be traced using simple surveying tools such as the A-frame level or the water tube level: workers begin on one edge of the hillslope and make their way across, marking out points which are at equal elevation. A curved line is then drawn between the points to represent the contour line (Fig. 7.2).

While this book provides only an introduction to the vast set of practices that fit the rainwater harvesting category, there are many freely available guides that provide the detailed information necessary to plan, size and construct common rainwater harvesting structures. A selection of these resources is listed in the further reading box at the end of the chapter.

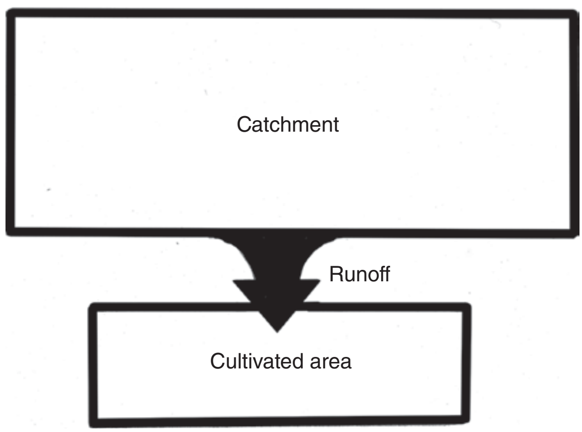

Fig. 7.1. Fundamental components of a rainwater harvesting structure.

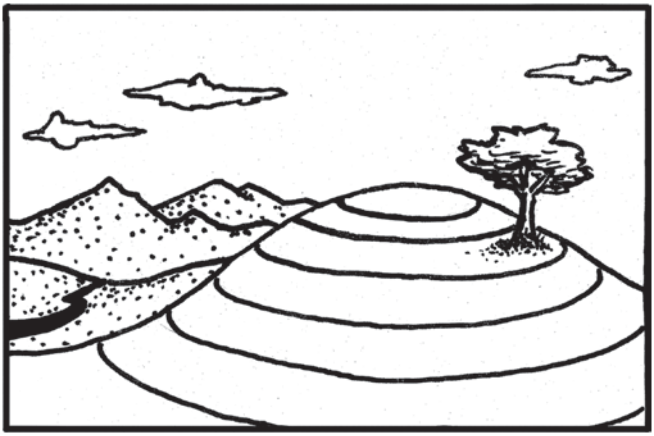

Fig. 7.2. Hillside contour lines.[4]

This chapter describes some common rainwater harvesting techniques and provides the information necessary to choose an appropriate approach for a given context. It covers topics spanning:

1. In-field rainwater harvesting.
2. Off-field rainwater harvesting.
3. Water storage structures and supplemental irrigation.

In-field Rainwater Harvesting

In-field rainwater harvesting involves intercepting runoff that originates within the field itself, and directing it toward a planted area for infiltration into the soil. In contrast, *off-field rainwater harvesting* involves diverting runoff from *outside* the field boundaries toward the field or into a storage structure for later use. In-field rainwater harvesting is usually cheaper and easier to implement than off-field techniques, making it more accessible to individual farmers on small farms.

In-field rainwater harvesting structures consist of a network of earthen *ridges, bunds, trenches and basins* designed to direct runoff from an in-field catchment toward a cultivated area (Fig. 7.3).

The general objective of water harvesting structures is to:

- keep runoff water on the field;
- slow down its trajectory; and
- encourage infiltration into the soil of the planted area.

This section describes the format and applicability of some widely used in-field water harvesting structures. Each category includes examples of regionally popular structures that have been successful in a given context. Although the names and descriptions of many of the listed structures originate in arid and semi-arid sub-Saharan Africa, functionally similar techniques are also practiced in other world regions, with some design variations according to climate and soil type.

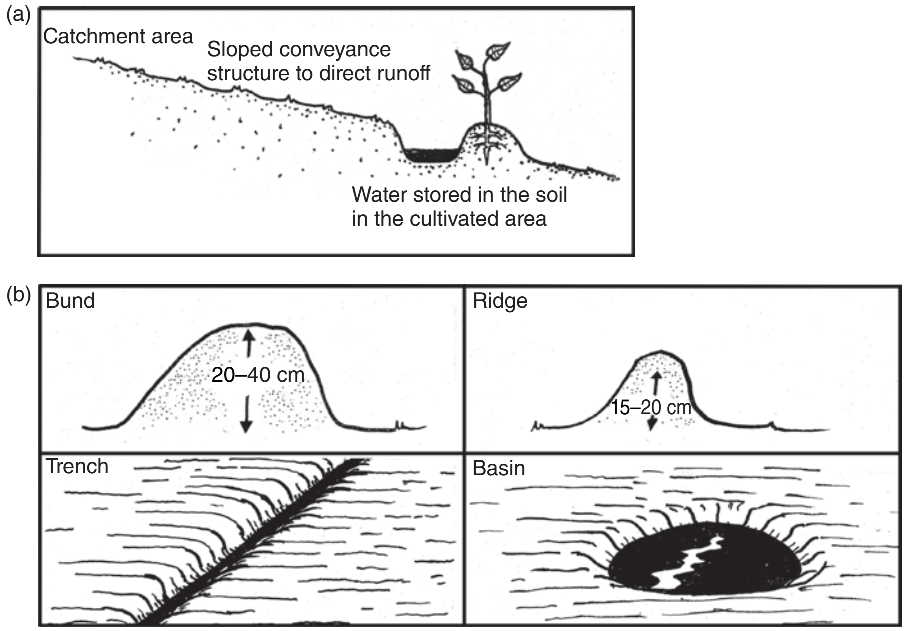

Fig. 7.3. (a) Basic elements of in-field rainwater harvesting (RWH). (b) Landforms used in RWH.

Microcatchments and pitting techniques

These rainwater harvesting techniques involve the creation of multiple *microcatchment* areas within the field itself. Microcatchments are small pockets of land created by building earthen embankments on gently sloping sites. Each microcatchment includes its own catchment area, designed to direct runoff toward a planted area at its downslope edge. *Planting pits* are variations on the microcatchment concept in which rainwater is collected within a shallow hole that is directly seeded. Pitting techniques are primarily used on dry, flat land to collect water running off impermeable or compacted soils.

Microcatchments are created through the establishment of a hillside network of bunds and basins. Bunds are built into the slope to slow and divert the flow of rainwater runoff, and basins installed behind them collect and infiltrate the captured water. Crops are grown either within basins (in arid regions with loose soils) or around their periphery (in regions where rains or soils are heavy and waterlogging is possible). Small basins where seeds are sown directly are called *planting pits* or *planting basins*. These pits are often filled with compost or manure to provide nutrient-rich microclimates for crop growth.

Pits and microcatchments are labor-intensive to construct, and their irregular planting layout can complicate the use of farm machinery. However, these techniques have good potential to improve yields and can provide opportunities for agriculture in areas with very low rainfall.

Some popular microcatchment and pitting techniques include *Zai* and *Ngoro* pits, *Demi-lunes,* and the *Negarim* planting technique (Figs 7.4–7.7).

i. Zai pitting technique[5,6,7,8]

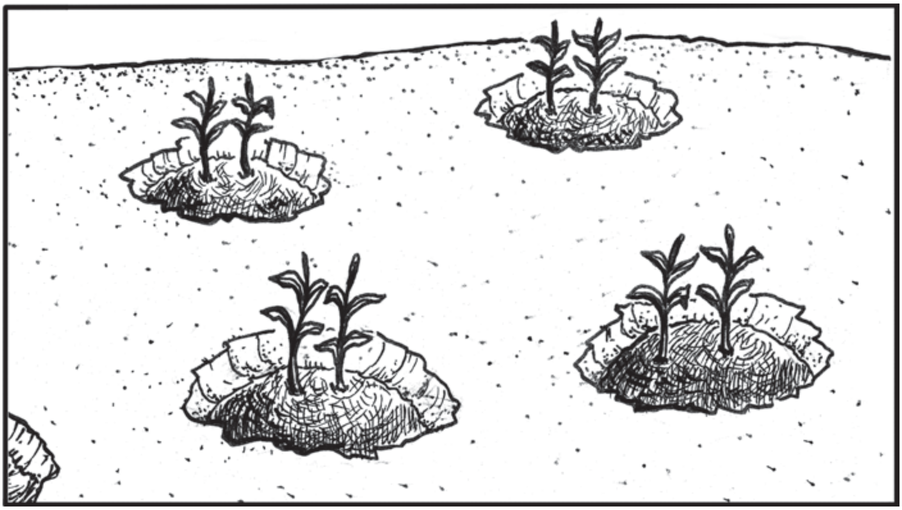

Fig. 7.4. Zai pits

Used with	Annual field crops
Basic design	Round pits surrounding field crops planted on flat lands, usually 5–25 cm deep, 15–50 cm in diameter, and spaced at least 80 cm apart. When installed on sloping land, pits should be aligned along the contour. Pits installed on sloped land can be coupled with low stone or earthen bunds on the downslope edge.
Favorable conditions	Flat land or shallow inclines (less than 2% slope) with clay or silt soils with poor infiltration (high runoff). Compacted or hardpan soils
Operation and maintenance	Pits are constructed during the dry season, and must be maintained each year. The establishment of pits in the first year can be labor-intensive, but maintenance much less so. Pits can be reused year after year, or alternated with new pits to allow a fallow period and restore soil fertility. Pits can be filled with compost to provide added nutrient benefit and encourage termite tunneling (for soil loosening). Plant residues can be added to the pit to absorb excess water in areas with a risk of waterlogging.
Areas of widespread use	Mali, Burkina Faso, Sahelian countries (especially Sudan), Zimbabwe
Similar techniques	*Tassa*, *Magun*, and *Dogon pits* are similar in concept to *Zai.* '*5 by 9 pits*' are 60 cm × 60 cm square pits planted with five or nine maize seeds in dry or wet areas, respectively. *Chololo pits* are bunded round pits approximately 22 cm in diameter and 30 cm deep installed on the contour. These pits are filled halfway with a mixture of manure, ash and plant residues, then covered with soil and planted with one or two seeds of millet, sorghum, or maize.

ii. Ngoro pitting technique[9,10]

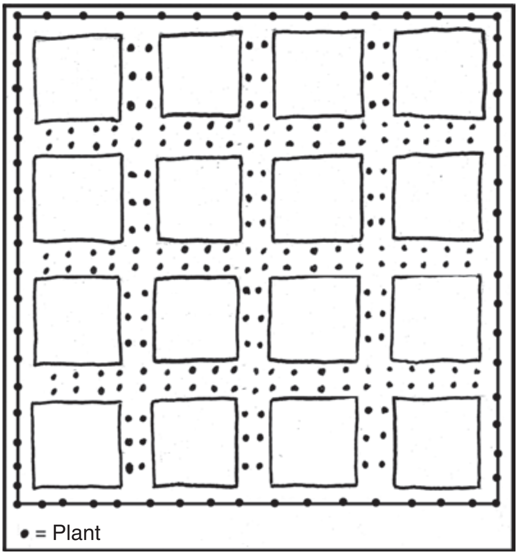

Fig. 7.5. Ngoro pitting technique.[11]

Used with	Annual field crops, especially maize/bean crop systems
Basic design	Square pits 1.5–2 m on each side and dug 10–50 cm deep, surrounded by ridges created by covering cut grass or ground-cover residues with excavated soil. Plants are grown along the top of the ridges. Buried residues provide added nutrients and help maintain the structure of the ridges.
Favorable conditions	Sloping lands (typically 20–50% slope) in semi-arid and sub-humid areas
Operation and maintenance	Grass or plant residues must be continually incorporated into the soil to replenish the ridges. The Ngoro system depends on fallow years to provide plant residues and regenerate soil. Traditionally, fallows of 6–7 years were common and these long fallow periods have provided the highest yields. More commonly, Ngoro is used in 2 year planting cycles, where a maize crop follows a rotation of legumes, wheat, or cassava.
Areas of widespread use	Tanzania (Matengo area)

iii. Demi-lunes (crescent-shaped bunds, semi-circular bunds)[12, 13]

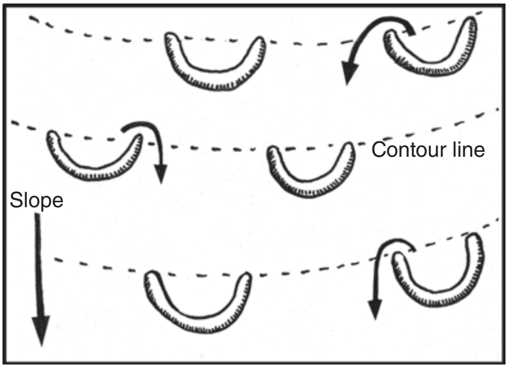

Fig. 7.6. Demi-lunes on a hillside.

Used with	Annual field crops, tree crops
Basic design	Demi-lunes are semi-circular bunds built along the contour of sloping land to intercept runoff running downhill. The upslope tips of the bunds are placed at equal height along the contour line so that each basin fills and overflows evenly. Rows of bunds are staggered so that a downhill bund will receive water from an overflowing bund in the row above it. Semi-circular bunds range from 2 m to 15 m in radius, depending on climate. Rows are typically spaced approximately one radius apart. Bund height can vary according to rainfall and soil type, but usually ranges from 15 cm to 25 cm. Crops are planted in the downslope tip of the demi-lune shape. Planting pits are used for demi-lunes planted with tree crops.
Favorable conditions	Gently sloping land in arid or semi-arid areas (200–800 mm annual rainfall)
Operation and maintenance	Bunds must be maintained each season to make sure they retain water and runoff is evenly distributed among demi-lunes.
Areas of widespread use	East Africa
Similar techniques	Trapezoidal bunds are based on the same concept, but are formed in the shape of a straight-walled open trapezoid. Trapezoidal bunds tend to be much larger and are compatible with farm machinery. Trapezoidal bunds are also used for off-field water harvesting.

iv. Negarim planting technique[14]

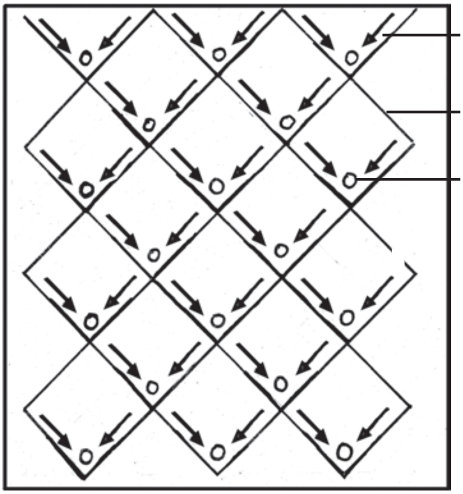

Fig. 7.7. Negarim planting technique with diamond-shaped catchment areas.[15]

Used with	Usually trees or bushes
Basic design	A Negarim microcatchment consists of a diamond-shaped catchment area surrounded by bunds and lined up along the contour. Runoff is directed from within the microcatchment toward a planting basin located at the downslope corner of the diamond shape. The Negarim system has been successful in supporting the cultivation of tree crops in very dry regions. The surface area of individual catchments ranges from 10 m^2 to 100 m^2, depending on species and rainfall conditions. Large Negarim are very labor-intensive to build. Bund height is at least 25 cm and higher on slopes greater than 5%.
Favorable conditions	Arid or semi-arid areas with as little as 150 mm annual rainfall
Operation and maintenance	Bunds are constructed by hand and must be maintained each season to ensure that they retain water effectively. Tillage and weed control must also be carried out manually since the layout of the Negarim prevents the use of farm machinery.
Areas of widespread use	Tunisia, Israel's Negev desert, arid and semi-arid areas of North Africa and sub-Saharan Africa
Similar techniques	V-shaped bunds are an open-sided variation of the Negarim technique. These have the advantage of allowing excess water to overflow toward other microcatchments, but they generally harvest less water than Negarim.

Contour farming

Contour farming is the general term for structures designed to create planting rows along the contour on sloping land. Contour farming, also sometimes known as contour plowing or contour furrows, is advantageous in that it arranges crops along the hillside in a way that allows them to intercept runoff evenly along their length. This layout also drastically reduces soil loss to erosion on sloping sites. Planting along the contour can reduce both runoff water loss and soil erosion by as much as 50%.[16] There are many forms of contour farming, which differ principally in the type of structure built to house crop plants along the slope. Popular methods of contour farming include contour bunds, terracing, and related techniques.

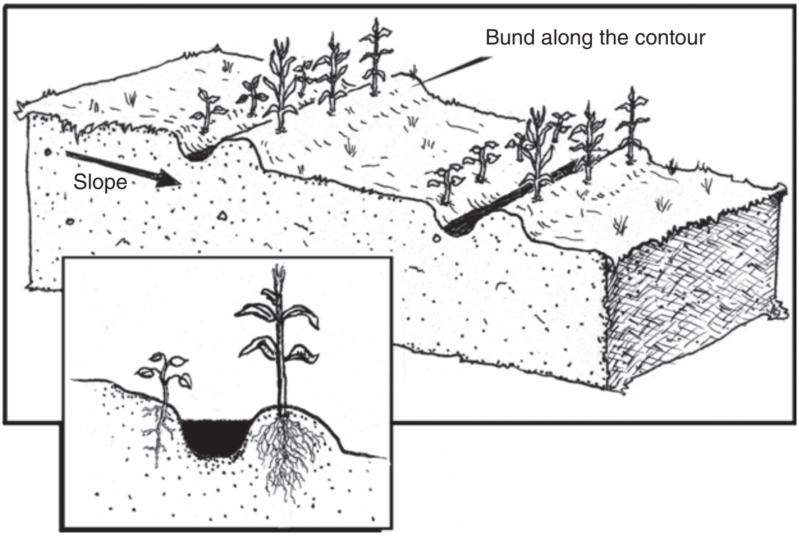

Fig. 7.8. Contour bunds.[17]

Contour bunds and ridges are used to create a favorable environment for crops on sloped sites (Fig. 7.8). They are constructed by digging out narrow trenches along the contour line and using the excavated soil to build a low bund along the trench's downslope edge. Runoff flowing downhill is trapped behind the bund and accumulates in the loosened soil of the trench. Crop rows are planted along the bund/ridge, close enough to the trench base to benefit from the water accumulation, but not so close as to become waterlogged during heavy downpours. Sometimes, a secondary crop is grown on the upslope edge of the trench as well. The remaining surface between ridges is not cultivated and serves as the runoff catchment area. Examples of popular rainwater harvesting techniques based on this concept include *tied contour ridges, stone bunds, trash lines,* and *retention ditches* (Figs 7.9–7.11).

i. Tied contour ridges[18,19]

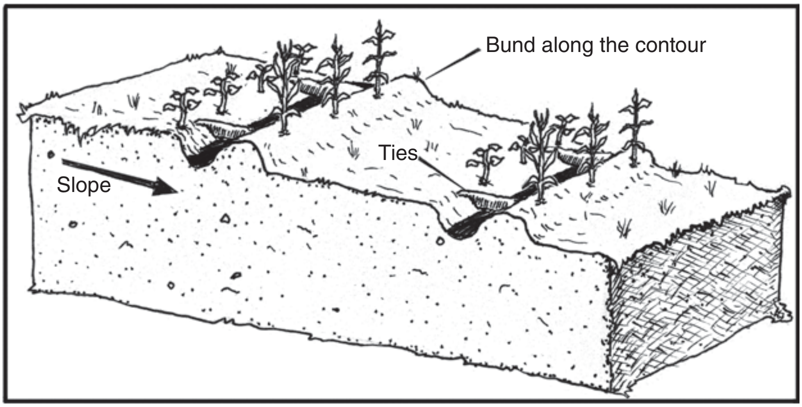

Fig. 7.9. Tied contour ridges.

Used with	Trees, grains, legumes, potatoes, bananas, other field crops
Basic concepts	A variation on the contour bund/ridge concept. In addition to the contour bund, short micro-ridges are installed at 4–5 m intervals within the base of the trench. These 'ties' are perpendicular to the contour and serve to prevent the lateral movement of water within the trench base. These ties effectively create small rectangular 'micro-basins' of water that is kept in place and allowed to infiltrate into the soil after a rain event. Because the low ridges may not be able to handle large volumes of runoff arriving from areas further up the slope, a wider diversion trench can be created uphill of the tied ridge installation to divert large overland flows.
Favorable conditions	Deep soil areas with 350–750 mm rainfall and even slopes of 0–5%
Operation and maintenance	Trenches are dug by hoe or using plows. Minimal maintenance is necessary if ridges are solidly constructed at the outset. If heavy rainfall causes water to flow over ridges, they should be built up higher.
Areas of widespread use	Kenya, Niger, Zimbabwe, and others. Tied ridges have been successful in improving banana crops in Uganda.

ii. Contour stone bunds (stone lines)[20,21]

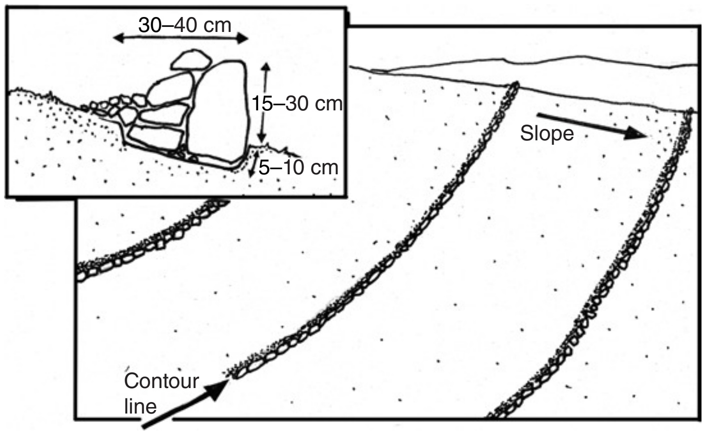

Fig. 7.10. Stone bunds.[22]

Used with	Most types of crops, often combined with Zai pits
Basic concepts	Contour stone bunds are very simple in design and inexpensive to construct. Lines of piled stone ('stone bunds' or 'stone lines') are laid across the contour on gently sloping fields to slow and spread runoff. Bund height will vary according to flow, but are similar to earthen bund heights at about 25 cm high and 35–40 cm wide at the base. Bunds are spaced between 15 m and 30 m apart, depending on the availability of stone and labor. Stone bunds intercept runoff arriving from uphill areas and force it to slow down and deposit loose soil behind the line of stone. This creates a favorable soil and water environment for plants upslope of the bund. A mixture of small and large rocks should be used in construction, with the smaller stones inserted into gaps on the upslope side of the bund.
Favorable conditions	Arid and semi-arid areas with 200–750 mm annual rainfall. Flat or gently sloping sites (less than 3% slope). Areas must have easy access to stones. Stone bunds have been successful in rehabilitating degraded land in high-runoff areas.
Operation and maintenance	Stones installed into a 5–10 cm deep trench at time of construction will be less prone to undercutting and bund damage during heavy rains. Bund stones may have to be repositioned after severe events, but generally maintenance is low. If bunds are prone to silting and blockage, small stones and silt should be cleared to make the bund slightly more permeable.
Areas of widespread use	West Africa, especially Burkina Faso

Continued

Continued.

Similar techniques	*Trash lines* are contour bunds made with crop residues instead of stones. Trash lines are popular in Kenya where they are typically spaced only a few meters apart. Crop residues will eventually degrade and return to build up the soil, so trash lines need to be rebuilt every few seasons. *Grass strips* are another variation that involve narrow strips of grass planted along the contour. These are effective in reducing erosion and retaining water but are not appropriate in very dry areas where soil water is insufficient to support both crops and grass.

iii. Retention ditches[23, 24]

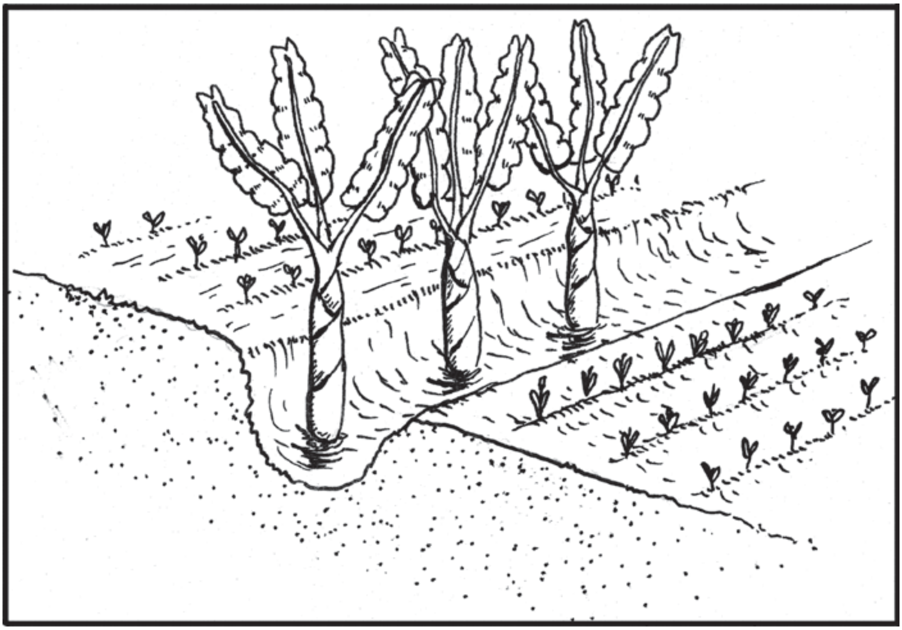

Fig. 7.11. Retention ditches.[25]

Used with	High-water-use crops
Basic concepts	Retention ditches are wide trenches (ditches) 0.5–1 m wide and 30–60 cm deep built along the contour. They can be used on flat or gently sloping sites where soil is well drained and not prone to caving in. Crop plants are cultivated along the base of the ditch. Retention ditches are a very simple structure used to allow the cultivation of high-water-use crops such as bananas in arid and semi-arid areas.

Continued

Continued.

Favorable conditions	Well-drained soil in arid and semi-arid areas
Operation and maintenance	Excavated soil should be used to reinforce trench sides, as these are prone to caving in. Ditches may need repair after heavy rains.
Areas of widespread use	Ethiopia

Terraces

Terraces are step-like structures built into a slope in order to create flat surfaces for crop cultivation. Terracing is an ancient farming practice that has allowed for agriculture to be practiced in highland areas. Conventional terraces, also known as *bench terraces*, are constructed by excavating deep into the slope and depositing excavated soil downhill to form a flat 'bench' surface supported by a sloped riser or wall (Fig. 7.12). The riser is sometimes reinforced by vegetation or piled stones. The surface of a bench terrace is either flat or graded slightly to drain inwards toward the uphill edge (in humid areas or as a water conservation structure) or outwards toward the terrace edge (in arid areas).[26,27] Terraces created for growing flooded crops such as rice are flat and protected at their edge by an impermeable shoulder bund.

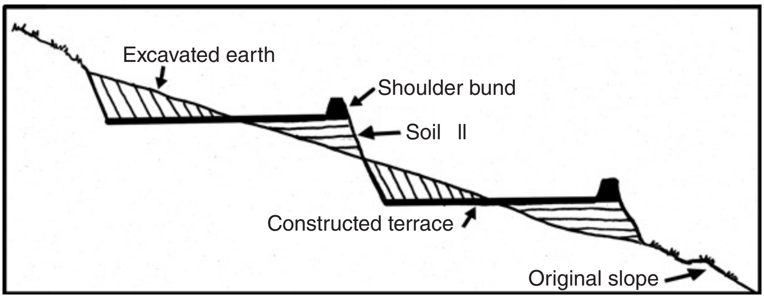

Fig. 7.12. Terrace creation.[28]

While conventional terraces are usually uniformly planted, terraces designed specifically for rainwater harvesting incorporate an uncultivated catchment surface that drains toward trenches or basins where water can collect and infiltrate on the terrace surface. Planting is concentrated near these infiltration areas, either within the trench/basin or along a low ridge, depending on soil and moisture conditions. Terraces can be very labor-intensive to construct, so the cost–benefit ratio of terracing should be carefully considered. If direct excavation is impractical, terraces can be gradually created with the help of rain runoff as soil builds up behind contour ridges or stone bunds after successive rain events. A good example is the fanya-juu system of Kenya, where rainwater harvesting structures promote the gradual formation of terraces on steep slopes (Fig. 7.13).

i. Fanya-juu terraces[29,30]

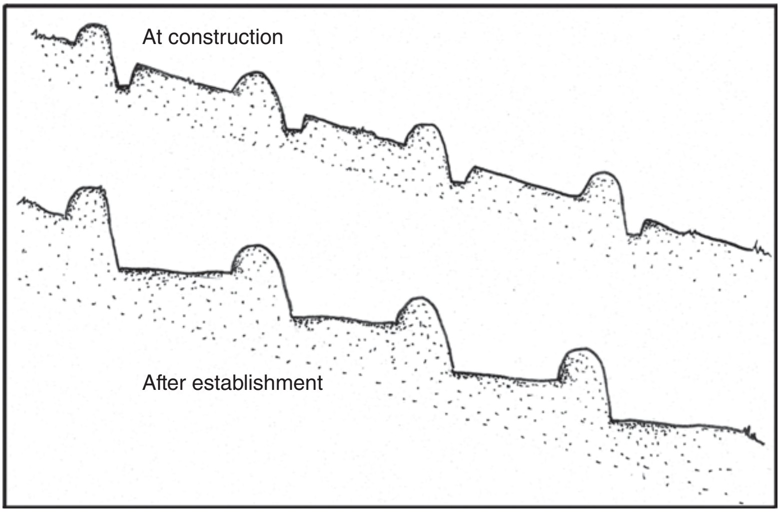

Fig. 7.13. Fanya-juu terraces at construction (top) and after establishment (bottom).[31]

Used with	All types of crops
Basic concepts	Fanya-juu terracing is a traditional Kenyan method for gradually building terraces into a hillside. A series of trenches 60 cm wide by 60 cm deep is first cut into the slope along the contour, and the excavated soil is thrown upslope of the trench to form an uphill bund about 50 cm high and 150 cm across at its base. The trench/bund combination is reinforced with each rain event as soil erodes off the slope and is deposited behind the bund. Gradually, the strip between the trenches becomes flat. Bunds are often reinforced with fodder grass, trees or bushes, and water-loving trees such as bananas can be grown in the trench bottom. The distance between trenches varies according to local conditions, but usually varies from 5 m on steep slopes to 20 m on gently sloped terrain.
Favorable conditions	Terrace construction requires deep, compactable soils. Fanya-juu terraces are common on steep slopes (5–50%) in areas with 500–1000 mm annual rainfall.
Operation and maintenance	The trench and bund must be reinforced each season. If excessive off-field runoff is problematic, stone walls should be built to reinforce the terraces.
Areas of widespread use	East Africa, Morocco
Similar techniques	*Conservation bench terraces* are wide terraces where some of the original slope is preserved on an the upslope strip of land. This part of the terrace serves as a catchment area, directing water toward a cultivated strip on the downslope side. *Fanya-chini* terraces are similar to Fanya-juu but are created by throwing excavated soil downslope of the trench.

Off-field Rainwater Harvesting

Off-field rainwater harvesting (also sometimes called *ex situ* or *long-slope* rainwater harvesting) involves channeling runoff originating from outside the field or even off the farm. Off-field rainwater harvesting is most successfully practiced on farms located downhill from surfaces that generate significant runoff during rain events, such as bare fields, rock surfaces, roads, or drainage channels. Large-scale diversion projects can even divert rainfall runoff from many kilometers away.

Off-field rainwater harvesting includes a range of scales of activity. At the individual farm scale, water is diverted from a catchment area located directly upstream of the field: these systems involve the construction of a network of ridges, trenches, bunds and basins designed specifically for the site based on careful observations of how water moves over the land during rain. Catchment surfaces can include roads, hills, and nearby forest or fields. If the catchment area is part of the farmer's land, it can be treated to produce maximum runoff by compacting the soil or adding an impermeable covering. This land can also be cleared of large plants to produce more runoff, but only in moderation because clearing can also expose the land to erosion by wind or water. Water runoff from the catchment surface is diverted to the field via a series of bunds, gullies and other landforms. Diverted water is then either infiltrated within a cultivated area, or directed toward surface or subsurface storage. Storage structures used for harvested runoff include surface reservoirs, ponds, underground tanks, and water storage dams.[32]

At the district scale, water diversion structures are erected in heavy runoff areas, intermittent streams or floodplains located within the wider watershed. These large-scale installations are usually collaborative ventures undertaken by farmers' organizations or local governments to serve more than one farm. In these cases, the catchment area can be up to 50 km^2, though most are less than 1 km^2 in size.[33] Drainage channels divert water runoff from heavy rain events through a conveyance network leading to a storage facility shared by several farmers. Some larger district-scale systems involve an extensive, formal drainage network of pipes or lined channels. In mountainous Afghanistan for example, snowmelt from upland areas is diverted through a vast network of underground channels to create oases in the desert where crops can be grown.[34]

Regardless of the method used, it must be recognized that there are limits to the practice of harvesting runoff. Water diversion is always a trade-off, and downstream users and ecosystems can be negatively impacted by the diversion of water higher up in the watershed. A stream or river that farmers depend on as a blue water source may be deprived of water if rain runoff is diverted on a large scale. Care must be taken to ensure that water diversion projects do not compromise overall watershed management objectives.

Bunds, trenches and other structures used to divert off-field rainwater harvesting are structurally similar but generally larger in scale than those used for in-field rainwater harvesting. Because the collection areas for these installations can be larger and steeper than those used in in-field harvesting, they must be built to withstand significant erosive forces. Most installations are custom-designed over a process of trial and error by observant farmers looking to seize opportunities for capturing runoff water in their area.

Off-field rainwater harvesting systems can be divided into two broad categories: (i) those that direct water directly onto a planted area for direct infiltration; and (ii) those that divert water into storage for later use. *Spate irrigation* is a closely related concept that includes structures that fit into both categories.

Water harvesting structures for direct infiltration

In these systems, rainwater cascading down a hill in sheet or rill flow is diverted and slowed to provide water for planted areas located within the hillside or at its base. Large planting areas enclosed by bunds are installed in strategic locations to receive both water and transported soil during rain events. Bunds installed for off-field rainwater harvesting are similar in shape to those used in *in situ* water harvesting, but much larger in size, often measuring more than 100 m across.[35] They are either constructed on-contour, with carefully designed spillways and flow-spreading structures to direct excess water, or at the receiving end of drainage gullies. Hillside structures for water harvesting date back to traditional agriculture, where bunds were constructed by hand to create opportunities for subsistence farming in arid lands. In some parts of the Sahel, large earthen bunds locally known as *teras* (Fig. 7.14, right) can make sorghum farming possible in areas receiving as little as 150 mm rainfall annually.[36] Similar bund systems are used in India, Pakistan, Brazil, and West Africa to create crop areas in dry, hilly landscapes.[37]

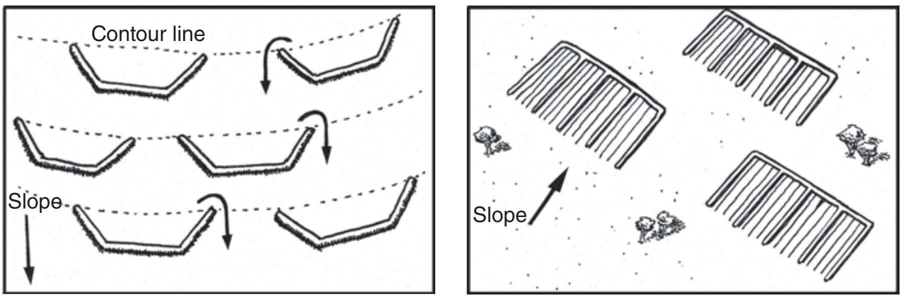

Fig. 7.14. Trapezoidal bunds (left) and teras bunds (right).[38]

Used with	A range of crops, trees, and grasses. Often used with grain crops
Basic concepts	A series of bunds, spillways and gullies are created to direct, slow and spread runoff water into flat planted areas. Trapezoidal bunds are constructed on contour with 'wings' spreading out at a 135° angle. Bunds are lined up so that excess runoff from one overflows into another downhill. The *teras* system uses rectangular, internally divided bunded planting areas. They are fed by either sheet flow or drainage gullies. In both types, uphill diversion structures and spreading bunds (rock bunds designed to spread out runoff water flow) can be used to provide even wetting across the planted area.

Continued

Continued.

Favorable conditions	Gently sloping hillsides or flat areas downhill from runoff-producing surfaces.
Areas of widespread use	Widely used traditional practice across North Africa and the Middle East, the Horn of Africa, West Africa, India, Pakistan, and some Latin American countries.[39]

Spate irrigation

Large-scale runoff diversion on a seasonal basis is known as *spate irrigation* (or *flood irrigation*) and is common practice in arid areas with substantial rainy season flooding. Spate irrigation is closely related to off-field rainwater harvesting, but involves structures specifically designed to redirect temporary stream flows that appear during periods of heavy seasonal precipitation.[40]

Diverting floodwaters from intermittent streams formed during rainstorms is an ancient practice that is still in widespread use in arid and semi-arid areas of South and West Asia, North Africa and the Middle East, and across the Horn of Africa. Some examples include the *majaluba* system of Tanzania and the *siham/kitea* system of Eritrea (Fig. 7.15).[41] Flood irrigation was also widely used in pre-Colombian South America, and some systems, like the *Waru-Waru* system of the high Andes, are now being reinvigorated with good results.[42]

Spate irrigation systems range in magnitude from diverting small drainage gullies to redirecting large seasonal rivers. Typically, these structures are composed of three elements: (i) a diversion structure designed to change the direction of flow; (ii) spate canals to carry the diverted water; and (iii) on-site bunds designed to spread and divide the flow around the farm. During flooded periods, one or a series of level planting areas are temporarily inundated while water infiltrates and is stored in the soil. Other systems involve the spreading of spate flows through a network of furrows like those used in surface irrigation (see Chapter 10).

Spate irrigation structures can be very labor-intensive to construct and are difficult to maintain, due to the strong erosive force of floodwaters and the changing pattern of sediment deposition along canals. These structures are often planned and built by a group of farmers for collective use. This allows farmers to share maintenance tasks, and eventually pool resources to purchase tools or machinery that can make maintenance and earth moving easier. The establishment of district-level spate irrigation schemes was the basis for the foundation of ancient agricultural communities in areas of North Africa and the Middle East.[43]

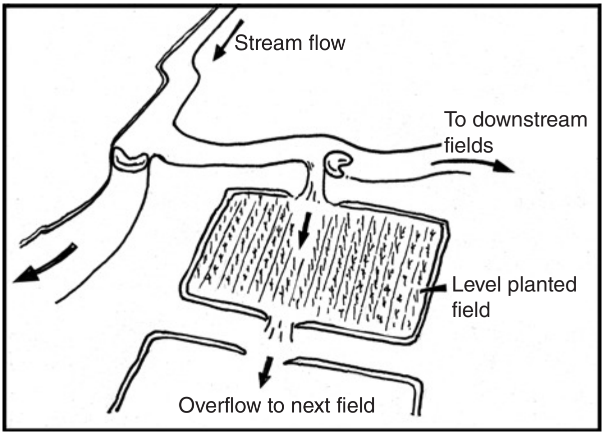

Fig. 7.15. Spate irrigated fields.[44]

Used with	Subsistence crops, especially grains
Basic concepts	Floodwater diverted from ephemeral streams and rivers is directed toward planted surfaces by a series of bunds. Bunds used for spate irrigation are large, often more than 5m high. They can be constructed from compacted earth or concrete. Planting occurs after first flood. Level basins and furrow systems are created for growing crops.
Favorable conditions	Planting is done on flat land or bunded hillsides downhill from runoff-producing headlands, or in proximity to intermittent streams. Used most in arid climates where flash flooding can occur before and/or during the growing season.
Areas of widespread use	North Africa and Middle East, Horn of Africa (Somalia, Sudan, Eritrea) and some Latin American countries[45]

Bunds and gullies for channeling runoff water into storage

Some rainwater harvesting schemes involve the diversion of runoff water toward storage structures instead of directly onto the planting field. This stored water supply is then used to provide *supplemental irrigation* during dry spells. Storage is most common in sub-humid zones with highly variable rainfall during the growing season. Because most storage structures are vulnerable to water loss, it is not usually possible to retain water from one season to the next.

Unlike those made for direct infiltration, rainwater harvesting structures used in conjunction with storage structures are designed to concentrate runoff flows (Fig. 7.16). Common components of such systems include large, cross-slope bunds fitted with strategically placed stone spillways that direct water flows into drainage gullies. Sloped, stone-filled trenches can also be installed across the contour of sloping lands in order to intercept sheet flow and transfer it toward a conveyance structure.[46]

These types of rainwater harvesting networks are site-specific and often undergo frequent re-design by the individuals or groups that manage them. Sediment deposition is a persistent issue for rainwater harvesting structures that involve storage instead of direct infiltration. Planted areas are able to make good use of deposited sediment, which helps build soil for cultivation. In the case of conveyance and storage structures, however, sediment is a nuisance that causes structures to fail without constant maintenance. Ideally, sediment filtration should be provided upstream of storage structures in order to minimize maintenance issues.

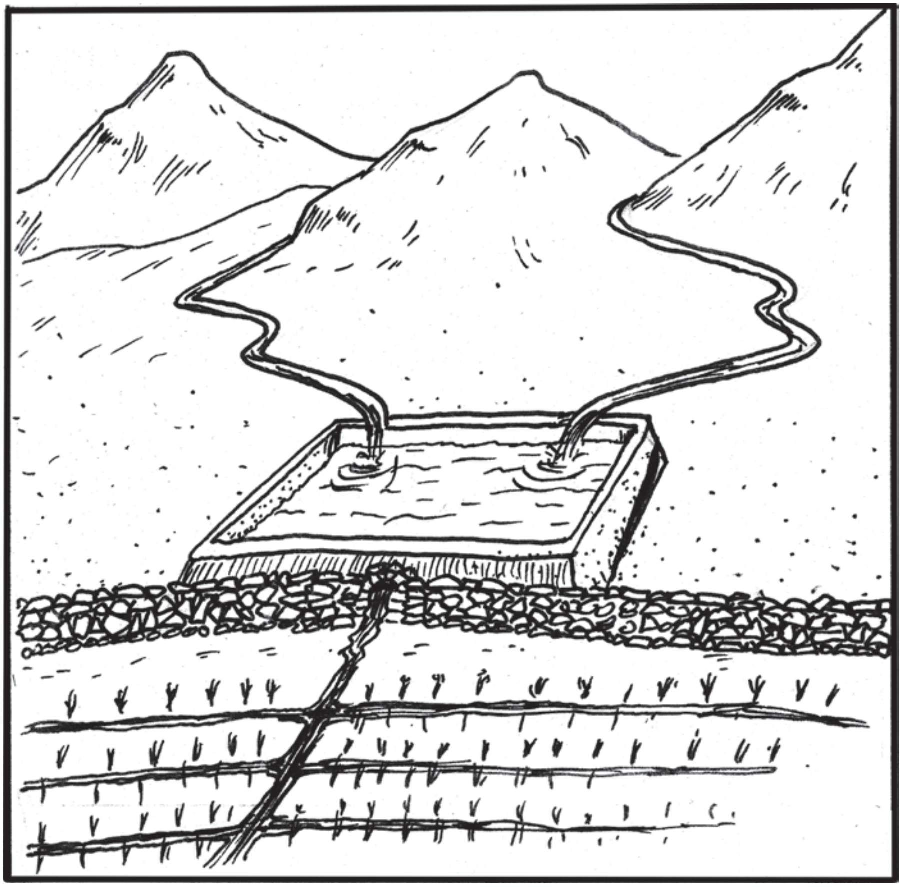

Fig. 7.16. Off-field water harvesting with storage structure.[47]

Water Storage

Storage structures for capturing runoff can include free-water structures such as ponds and cisterns, and soil-water capture structures that store water in the upper layers of the soil.

Farm ponds

The simplest water storage structures are open farm ponds. These are excavated earthen depressions sited to receive water from an uphill runoff-producing catchment area. The size of farm ponds varies depending on the catchment area feeding it: volumes ranging from 100 m^3 to 500 m^3 are common.[48] Open ponds are typically very inefficient, owing to excessive water losses to both evaporation and seepage. In unlined ponds made with compacted earth, seepage losses alone can waste up to 70% of the harvested water.[49] Evaporation is also a major source of inefficiency in hot dry climates, so storage structures should be designed to minimize the free water surface area. Storage ponds that collect sediment-rich runoff will gradually fill with silt. Silt management is therefore critical in order to maintain storage capacity.

Improved ponds/tanks and underground cisterns

Pond structures can be *improved* by lining the bottom with an impermeable liner, typically made from plaster, clay, concrete, or plastic. Some examples include the *berkads* of East Africa and India's irrigation *tanks*, which are variations of lined ponds. *Cisterns*, covered water structures created using the same materials, are even less susceptible to evaporation losses. Lining and cover materials can be quite expensive unless they are in abundant supply locally: for example, termite-mound earth has been used as an affordable material for sealing storage tanks in Ethiopia.[50] Otherwise, sealing farm ponds can be prohibitively expensive for individual farmers considering the relatively small volumes of water that can be retained.

Small earth dams

When a farm is located near a Small watercourse or intermittent stream, there is also the option of building low dams in order to retain water flow and generate a reserve of water for irrigation, livestock, or domestic uses. Small earth dams are built within intermittent stream beds using the earth excavated for the formation of an upstream reservoir. Curved-wall dams can also be built into hillsides to capture runoff. Ponds built within natural depressions that intercept runoff are also types of dams.[51]

Earth dams can be constructed manually using locally available materials, and are therefore well suited to the small farmer. Hand-made earth dams should not exceed 5 m in height, when measured from stream bed to the top of the dam wall.[52] Typically, a dam will include three elements: (i) dam wall; (ii) embankment protection; and (iii) an overflow weir. If the dam will intercept water from a catchment area exceeding 25 km^2, or if is to be located in areas characterized by extremes of drought and/or flash flooding, it should be constructed with the help of a qualified specialist.[53]

Subsurface dams

Another way to store water is within the top layers of earth: the soil is a free, unlimited storage structure that can be easily manipulated. Even when riverbeds are dry, often there is water not far from the surface, as indicated by plants and trees growing along the banks. Subsurface dams are underground barriers erected across dry or intermittent watercourses to allow underground water to temporarily pool up behind them. They consist of low walls made of masonry, stone or concrete laid perpendicularly across the streambed, dug deep enough to intercept the shallow water table running just under the surface. Stored water can be drawn off through a pipe installed through the dam wall, or pumped out of the saturated ground upstream of the dam.[54] Subsurface dams store water more efficiently than surface varieties because evaporation is reduced significantly. The stored water also stays cleaner and is protected from animals and pests.[55]

Sand dams

Sand dams are a special type of subsurface dam used in arid areas with intermittent rivers that carry large amounts of sand and soil. A low wall is erected across the dry riverbed to intercept the water flow when the stream begins to flow in the wet season (Fig. 7.17). As water builds up behind the dam, coarse sand particles, soil and rocks will settle out, building up a layer of deposited sand behind the dam and creating a sand-filled land area that is rich in subsurface water. The dam structure can be built up successively higher before each rainy season in order to gradually increase storage capacity. The water stored in the sand is protected from both

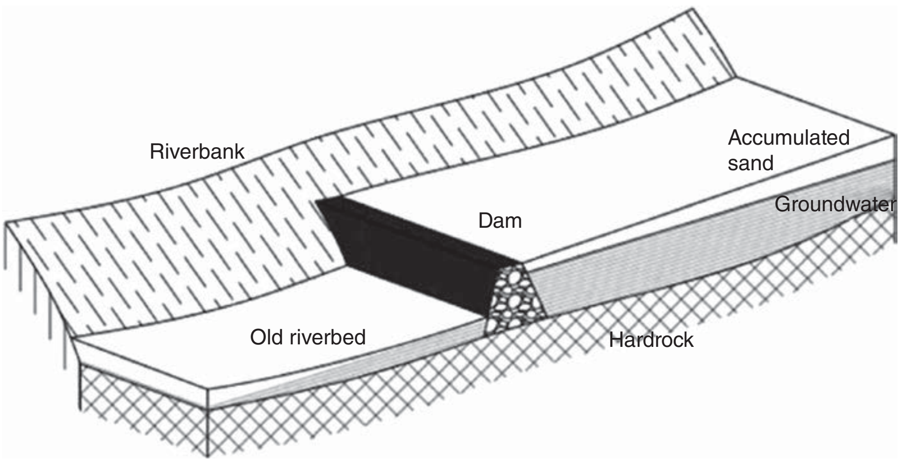

Fig. 7.17. Sand dam.

evaporation and contamination by animals. Water inside the dam can be accessed through an outlet pipe (protected by a filter) or pumped out through a shallow well.[56] Water from subsurface dams is used primarily for domestic purposes, but can also support small-scale supplemental irrigation schemes.[57] In order to avoid leakage, subsurface and sand dams should be sited and designed with the help of someone who has experience with these structures.

With all interception structures, care should be taken to ensure that downstream users of the same watercourse will not be adversely affected by changes in the flow pattern. If other farmers are dependent on the same watercourse for their own supply, diversion structures and dams could be a source of conflict.

Supplemental irrigation

Water collected in storage-based rainwater harvesting systems is used in a variety of ways: for domestic uses, to water livestock or to support crops through *supplemental irrigation*. Because water storage volumes are typically small to moderate (less than 500 m^3), harvested rainwater is generally insufficient to provide field crops with full irrigation. It is instead used as a backup supply for supporting normally rainfed crops during dry periods. Groundwater and surface water supplies can also be used to supply water for supplemental irrigation when they are available.

Supplemental irrigation is distinct from full irrigation in that:

- It is applied to crops that otherwise would be entirely rainfed.
- It does not on its own supply the full crop water requirement.
- It is only applied when needed, not on a regular basis.

By applying water as supplemental irrigation during dry spells, farmers can mitigate the harmful effects of water stress during critical plant growth stages. Supplemental irrigation has been shown to significantly improve water productivity in rainfed situations, even providing similar yields as fully irrigated plots.[58] Rainfed crops supplied with supplemental irrigation benefit from less time spent in a condition of water stress, which is especially beneficial when dry periods coincide with high-water-demand growth stages such as flowering or grain filling. If water is available early in the season, supplemental irrigation can also be used to support early sowing, which can significantly improve yields in some cases.[59]

Supplemental irrigation is applied in a variety of ways, depending on the location of the reservoir and the type of crop. Methods for providing both supplemental and full irrigation are covered in Chapter 10, and scheduling water applications is discussed in Chapter 11.

Further reading – Rainwater harvesting and spate irrigation

Soil and Water Conservation with a Focus on Water Harvesting and Soil Moisture Retention, a study guide by FARMESA. Available at: www.share4dev.info/kb/documents/1950.pdf

Sourcebook of Alternative Technologies for Freshwater Augmentation in Africa, by the United Nations Environment Programme (UNEP). Available at: www.unep.or.jp/ietc/publications/techpublications/techpub-8a/

Sourcebook of Alternative Technologies for Freshwater Augmentation in Latin America and the Caribbean, by UNEP. Available at: http://www.unep.or.jp/ietc/Publications/techpublications/TechPub-8c/rooftop.asp

Agrodok 13: Water harvesting and soil moisture retention, produced by the Agromisa Foundation. Available at: www.agromisa.org

Water Harvesting and Conservation, produced by the Henry Doubleday Research Association (HDRA). Available at: www.gardenorganic.org.uk

Water Harvesting: A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production, by W. Critchley and K. Siegert, produced by the Food and Agriculture Organization of the United Nations (FAO). Available at: www.fao.org/3/a-u3160e/index.html

Guidelines on Spate Irrigation, produced by the FAO. www.fao.org/docrep/012/i1680e/i1680e00.htm

Rainwater Harvesting: A Lifeline for Human Well-being, booklet by UNEP. Available at: www.unwater.org/downloads/Rainwater_Harvesting_090310b.pdf

Rain Catchment and Water Supply in Rural Africa: A Manual, by E. Nissen-Petersen. Available at: www.ircwash.org/sites/default/files/213.0-82RA-166.pdf

References

1 Bot, A. & Benites, J., 2005. *The Importance of Soil Organic Matter*. Rome: Food and Agriculture Organization of the United Nations (FAO), p. 35.

2 Critchley, W. & Siegert, K., 1991. *Water Harvesting*. Rome: FAO, p. 6.

3 Anschütz, J. *et al*., 2003. *Water Harvesting and Soil Moisture Retention*, M. Nederlof & J. Anschütz, eds. Wageningen, The Netherlands: Agromisa Foundation, p. 3.

4 Adapted from Henry Doubleday Research Association (HDRA), unknown date. *Water Harvesting and Conservation*. Coventry, UK: HDRA, p. 5.

5 United Nations Environment Programme (UNEP), 1999. *Sourcebook of Alternative Technologies for Freshwater Augmentation in Africa. unep.or.jp.* Available at: http://www.unep.or.jp/ietc/publications/techpublications/techpub-8a/ [Accessed September 26, 2012].

6 Lee, M.D. & Visscher, J.T., 1990. *Water Harvesting in Five African Countries*. The Hague, The Netherlands: IRC International Water and Sanitation Centre.

7 Anschütz, J. *et al*., 2003. *Water Harvesting and Soil Moisture Retention*, M. Nederlof & J. Anschütz, eds. Wageningen, The Netherlands: Agromisa Foundation, p. 71.

8 Mati, B.M., 2005. *Overview of Water and Soil Nutrient Management under Smallholder Rain-fed Agriculture in East Africa*. Working paper 105. Colombo: International Water Management Institute (IWMI), p. 94.

9 Malley, Z. *et al*., 2004. Ngoro: an indigenous, sustainable and profitable soil, water and nutrient conservation system in Tanzania for sloping land. *Soil and Tillage Research*, 77, pp. 47–58.

[10] Mati, B.M., 2005. *Overview of Water and Soil Nutrient Management under Smallholder Rain-fed Agriculture in East Africa*. Working paper 105. Colombo: IWMI.
[11] Diagram adapted with permission from Malley, Z. *et al*., 2004. Ngoro: an indigenous, sustainable and profitable soil, water and nutrient conservation system in Tanzania for sloping land. *Soil and Tillage Research*, 77, pp. 47–58.
[12] UNEP, 1999. *Sourcebook of Alternative Technologies for Freshwater Augmentation in Africa*. *unep.or.jp*. Available at: http://www.unep.or.jp/ietc/publications/techpublications/techpub-8a/ [Accessed September 26, 2012].
[13] Anschütz, J. *et al*., 2003. *Water Harvesting and Soil Moisture Retention*, M. Nederlof & J. Anschütz, eds. Wageningen, The Netherlands: Agromisa Foundation, p. 71.
[14] Critchley, W. & Siegert, K., 1991. *Water Harvesting*. Rome: FAO.
[15] Diagram adapted with permission from Critchley, W. & Siegert, K., 1991. *Water Harvesting*. Rome: FAO.
[16] Anschütz, J. *et al*., 2003. *Water Harvesting and Soil Moisture Retention*, M. Nederlof & J. Anschütz, eds. Wageningen, The Netherlands: Agromisa Foundation, p. 71.
[17] Diagram adapted from Anschütz, J. *et al*., 2003. *Water Harvesting and Soil Moisture Retention*, M. Nederlof & J. Anschütz, eds. Wageningen, The Netherlands: Agromisa Foundation, p. 71.
[18] Mati, B.M., 2005. *Overview of Water and Soil Nutrient Management under Smallholder Rain-fed Agriculture in East Africa*. Working paper 105. Colombo: IWMI, p. 94.
[19] Critchley, W. & Siegert, K., 1991. *Water Harvesting*. Rome: FAO.
[20] Ibid.
[21] Anschütz, J. *et al*., 2003. *Water Harvesting and Soil Moisture Retention*, M. Nederlof & J. Anschütz, eds. Wageningen, The Netherlands: Agromisa Foundation, p. 71.
[22] Diagram adapted with permission from Critchley, W. & Siegert, K., 1991. *Water Harvesting*. Rome: FAO.
[23] HDRA, unknown date. *Water Harvesting and Conservation*. Coventry, UK: HDRA.
[24] Duveskog, D. *et al*., 2003. *Soil and Water Conservation with a Focus on Water Harvesting and Soil Moisture Retention*, 1st edn. Harare: FARMESA, p. 7.
[25] Adapted from Duveskog, D. *et al*., 2003. *Soil and Water Conservation with a Focus on Water Harvesting and Soil Moisture Retention*, 1st edn. Harare: FARMESA.
[26] Singh, R.P. *et al*., 1990. *Field Manual on Watershed Management*. *fao.org*. Available at: http://www.fao.org/docrep/006/t0165e/t0165e00.HTM [Accessed November 14, 2015].
[27] Mati, B.M., 2005. *Overview of Water and Soil Nutrient Management under Smallholder Rain-fed Agriculture in East Africa*. Working paper 105. Colombo: IWMI.
[28] Adapted from FAO, 1989. *Watershed Management Field Manual: Slope Treatment Measures and Practices*. Rome: FAO.
[29] Mati, B.M., 2005. *Overview of Water and Soil Nutrient Management under Smallholder Rain-fed Agriculture in East Africa*. Working paper 105. Colombo: IWMI.
[30] UNEP, 1999. *Sourcebook of Alternative Technologies for Freshwater Augumentation in Africa*. *unep.or.jp*. Available at: http://www.unep.or.jp/ietc/publications/techpublications/techpub-8a/ [Accessed September 26, 2012].
[31] Adapted from UNEP, 1999. *Sourcebook of Alternative Technologies for Freshwater Augumentation in Africa*. *unep.or.jp*. Available at: http://www.unep.or.jp/ietc/publications/techpublications/techpub-8a/ [Accessed September 26, 2012].
[32] Biazin, B. *et al*., 2011. Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa – a review. *Physics and Chemistry of the Earth*, 47–48, pp. 1–13.
[33] Ibid.
[34] Harrington, L. & Tow, P., 2011. Types of rainfed farming systems around the world, in P. Tow *et al*., eds, *Rainfed Farming Systems*. Dordrecht, The Netherlands: Springer, p. 54.
[35] Critchley, W. & Siegert, K., 1991. *Water Harvesting*. Rome: FAO.

[36] UNEP, 1999. *Sourcebook of Alternative Technologies for Freshwater Augumentation in Africa*. *unep.or.jp*. Available at: http://www.unep.or.jp/ietc/publications/techpublications/techpub-8a/ [Accessed September 26, 2012].

[37] Barron, J. & Salas, J.C., 2009. *Rainwater Harvesting: a Lifeline for Human Well-being*. Nairobi: UNEP/Stockholm Environment Institute (SEI).

[38] Critchley, W.R.S. & Reij, C. (1989) Water harvesting for plant production: part 2. Case studies and conclusions from sub-Saharan Africa. (Draft). To be published in 1991 as the final report of the World Bank's Sub-Saharan Water Harvesting Study.

[39] Source: (i) UNEP, 1999. *Sourcebook of Alternative Technologies for Freshwater Augmentation in Africa*. *unep.or.jp*. Available at: http://www.unep.or.jp/ietc/publications/techpublications/techpub-8a/ [Accessed September 26, 2012]; and (ii) Critchley, W. & Siegert, K., 1991. *Water Harvesting*. Rome: FAO.

[40] Falkenmark, M. *et al*., 2001. *Water Harvesting for Upgrading of Rainfed Agriculture*. Stockholm: Stockholm International Water Institute (SIWI), p. 94.

[41] van Steenbergen, F. et al., 2010. *Guidelines on spate irrigation. FAO Irrigation and Drainage Paper 65,* Rome: FAO.

[42] Altieri, M.A., 1999. Applying agroecology to enhance the productivity of peasant farming systems in Latin America. *Environment*, 1(3/4), p. 206.

[43] Stockle, C.O., 2001. *Environmental Impact of Irrigation: a Review*. Pullman, Washington: State of Washington Water Research Center.

[44] Diagram adapted with permission from van Steenbergen, F. et al., 2010. *Guidelines on spate irrigation. FAO Irrigation and Drainage Paper 65,* Rome: FAO.

[45] Source: (i) Falkenmark, M. *et al*., 2001. *Water Harvesting for Upgrading of Rainfed Agriculture*. Stockholm: SIWI, p. 94; and (ii) van Steenbergen, F. et al., 2010. *Guidelines on spate irrigation. FAO Irrigation and Drainage Paper 65,* Rome: FAO.

[46] Rosegrant, M.W. *et al*., 2002. *The Role of Rainfed Agriculture in the Future of Global Food Production*. Washington, DC: International Food Policy Research Institute.

[47] Adapted from Duveskog, D. *et al*., 2003. *Soil and Water Conservation with a Focus on Water Harvesting and Soil Moisture Retention*, 1st edn. Harare: FARMESA, p. 10.

[48] Humphreys, E. *et al*., n.d. *Improving Rainwater Productivity.* Available at: http://r4d.dfid.gov.uk/PDF/Outputs/WaterfoodCP/Improving_Rainwater_Productivity%5B1%5D.pdf [Accessed June 10, 2016].

[49] Fox, P. & Rockström, J., 2003. Supplemental irrigation for dry-spell mitigation of rainfed agriculture in the Sahel. *Agricultural Water Management*, 61(1), pp. 29–50.

[50] Biazin, B. *et al*., 2011. Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa – a review. *Physics and Chemistry of the Earth*, 47–48, pp. 1–13.

[51] Nissen-Petersen, E., 2006. *Water from Small Dams*. Copenhagen: Danish International Development Assistance (Danida).

[52] Stephens, T., 2010. *Manual on Small Earth Dams: a Guide to Siting, Design and Construction*. Rome: FAO, p. 1.

[53] Ibid.

[54] Wateraid, 2011. *Technology Notes*. London: Wateraid. *wateraid.org*.

[55] Ibid. Diagram adapted from Friends of Kitui, n.d. Helping to bring about change. *friendsofkitui.com.* Available at: http://www.friendsofkitui.com/water_harvesting.html [Accessed October 2, 2015].

[56] Wateraid, 2011. Technology Notes. London: Wateraid. wateraid.org.

[57] Ibid.

[58] Oweis, T. *et al*., 1999. *Water Harvesting and Supplemental Irrigation for Improved Water Use Efficiency in Dry Areas*. Colombo: IWMI.

[59] Ibid.

8 Crop-focused Strategies: Using Available Water Wisely

The plant also has a role to play in water productivity. Crop management techniques can enhance the plant's ability to use soil water efficiently, further reinforcing the benefit of the soil and water management practices described in Chapters 6 and 7. Cropping systems can also be designed to encourage drought resistance and mitigate the harmful effects of dry periods. Drought resistance ultimately improves water productivity because it increases the potential for producing crop yields in seasons disrupted by dry spells.

Cropping patterns have a considerable impact on water productivity. Crop layouts and plant combinations can be calibrated to produce a maximum amount of product (or income) from within available water supplies. Often, this involves rotating between different plant varieties with complementary water and nutrient requirements.

Drought resistance can also be enhanced by selecting drought-resistant cultivars, and by training the physiological adaptation mechanisms of existing crops to access scarce soil water or improve the efficiency of the conversion process that transforms it into product.

The crop techniques described in this chapter include:

- crop choice;
- cropping patterns for efficient water use; and
- encouraging the natural adaptation of plants to dry conditions.

Crop Choice

Crop varieties are traditionally selected based on their ability to produce good yields under local rainfall and soil conditions. Crop water requirements should be closely matched with available rainfall – if there is a bad match, the farmer will always be chasing after more water than the clouds can provide.

Crop water requirements vary by climate and by cultivar (see Chapter 4). The range of water requirements for some major crops is given in Table 4.4 and repeated in Table 8.1. Recall that not all rainfall becomes available soil water – in situations characterized by unfavorable rainfall partitioning among water uses, the proportion of rainfall that becomes soil moisture stored in the root zone is well under half of the total annual value. This is compensated by the fact that crops are routinely cultivated with less than their full water requirement. Some degree of soil water deficit is virtually inevitable in dryland farming.

Switching crops, or changing variety of the same crop, can require a large initial investment. If the change results in higher yields, this investment can be quickly recouped. However, if the new crop is not immediately successful, the loss of both the initial investment and seasonal harvest revenues can represent a significant setback. Crop choices should be informed by past experiences of successful yields in a similar context. In today's agricultural landscape, farmers must also be wary of seed companies trying to make profit from the sale of new seed varieties that may or may not perform as well as advertised in local conditions. Consulting with local farmers' organizations and learning from the experiences of others working in the same region (or a similar climate and soil type) is invaluable in this process. It is also informative to try planting a small stand of the new crop on one part of the field as a test plot, to ensure it will grow well before changing the entire field.

To minimize risk, crops should only be chosen if seeds and required inputs are readily, cheaply and consistently available on the local market, and sales channels for the end product are well established. Intercropping of two or more crops with varying water requirements can be useful in areas with highly variable rainfall, as it increases the probability of getting at least at least one harvest even in difficult years.

Some crops are less sensitive to dry conditions than others, either because they are fast maturing, or because they are good at retaining water in their tissues as a backup supply. Given that global climate change will only exacerbate rainfall variability in the years to come, it is prudent to shift toward crop varieties that are least sensitive to periodic drought and dry spell conditions. The relative drought sensitivities of some major crops are given in Table 8.1.

One promising recent development in agricultural research is the development of so-called *drought-tolerant* crop varieties that are better able to withstand dry periods. Drought-tolerant varieties feature traits such as rapid development, improved tolerance to water stress during critical growth stages, and deep rooting depths (to reach wetter layers of soil).[2] Drought-tolerant varieties of major crops including rice, maize and wheat are already in widespread use worldwide. This is a relatively new area of research, however, and introduced seed varieties should be welcomed with a healthy degree of caution. Sustained local testing with new crop varieties is crucial to ensure that they can produce good and reliable yields within the context of local farming practices and environmental conditions.

Table 8.1. Relative drought sensitivity of some major crops.[1]

Crop	Sensitivity to drought	Crop water requirement (mm/season)
Banana	High	1200–2200
Barley/oats/wheat	Low/medium	450–650
Beans	Medium/high	300–500
Cabbage	Medium/high	350–500
Citrus	Low/medium	900–1200
Cotton	Low	700–1300
Groundnut (peanut)	Low/medium	500–700
Lucerne (alfalfa)	Low/medium	800–1600
Maize	Medium/high	500–800
Onion	Medium/high	350–550
Pea	Medium/high	350–500
Pepper	Medium/high	600–900
Potato	High	500–700
Rice (paddy)	High	450–700
Sorghum/millet	Low	450–650
Soybean	Low/medium	450–700
Sugarbeet	Low/medium	550–750
Sugarcane	High	1500–2500
Sunflower	Low/medium	600–1000
Tomato	Medium/high	400–800

The engineering of new crop varieties has accelerated in recent decades. A significant proportion of yield improvements achieved during the 'green revolution' era of the 1960s–1980s was attributed to the development of new, high-yielding crop varieties.[3] However, most of the high-yield varieties of the green revolution era were developed to be used in conjunction with a suite of costly inputs, including fertilizers, herbicides, and machinery. These types of seed are not-well suited to the low-income smallholder because of financial constraints.[4] Small farmers should be wary of seed varieties that require the purchase of auxiliary products to succeed.

Recent commercial seed development initiatives have focused on drought-tolerance as a means of improving the production capacity of common crops in water-stressed conditions. This is indeed an important objective, considering the urgent need to produce more food under increasingly variable climate conditions and scarce water. To date, much of this work has focused on producing seed for use in high-input commercial farming, so many of these new drought-tolerant varieties are so far also poorly suited to smallholder famers.[5] National and regional non-profit research pursuing the enhancement of drought resistance in local seed varieties is also ongoing, though generally at a slower pace than commercial seed development. In-country and regional research initiatives that focus on the adaptation of local seed varieties to promote drought tolerance are especially important in improving the seed stocks of smallholder farming communities.[6]

Farmers are key contributors to seed research as well: seed saving and swapping with neighbors is the best way to develop a diverse seed stock of varieties that have proven successful in the local climate.[7] Traditional mixed-crop systems used before the spread of commercial agriculture were inherently resilient to climate variations, and there is yet much to be learned from these models.[8] Maintaining a high degree of genetic diversity in local seed banks, exchanging seeds and knowledge with other farmers, and conserving traditional seed varieties are crucial tools for enhancing resilience in an uncertain climate.

Because investing in new crop varieties can be costly for small farmers, improving soil and water management practices to first reduce vulnerability to climate-related risk should provide a better cost–benefit in the short term for farmers looking to improve rainfed yields.[9]

Cropping Patterns for efficient water use

Crop rotations should be designed to make good use of available water by working with local rainfall patterns. Sometimes the soil will have excess available water during the rainy season, creating an opportunity to include a second crop or produce a cover crop. If the rainy season is long, there may be time for a second crop after the primary one has been harvested. In many parts of the tropics there are two rainy seasons, creating opportunity for two or more different crops in the same year. The timing of sowing and weeding can also be manipulated to make good use of soil water.

Some cropping patterns that promote the efficient use of available rainwater include: (i) intercropping; (ii) strip cropping; and (iii) relay cropping.

Intercropping

Intercropping is the practice of growing more than one crop simultaneously on the same field. Intercropping patterns promote water use efficiency by increasing the density of the plant canopy, reducing evaporation, and providing added competition to discourage weed growth. It is most effective if companion crops are chosen for non-competitiveness and beneficial interaction in terms of nutrient use, ground cover, structure, or shading. A traditional example is the maize–bean complex widely used across South America: in this system, bean plants fix nitrogen into the soil to benefit the maize, while the maize stalk provides shade and structure for the tender-leaved bean plants. Since maize roots grow to a greater depth than those of bean plants, there is minimal competition for soil water and nutrients between the two species. Other successful combinations in widespread use in dryland areas include millet intercropping with cowpea, sorghum, maize, or groundnut.[10]

Intercropping low-water use crops with higher-yielding, high-water counterparts can increase the overall efficiency of the water stored in the soil. This also provides an insurance plan in case the main crop suffers or fails. Seeding should be timed so that the crops will not achieve peak water use (peak K_c coefficients, as shown in Table 4.3) at the same time.

Strip cropping

Strip cropping is an intercropping pattern that also functions as a rainwater harvesting technique (Fig. 8.1). It involves the cultivation of wide strips of land laid along the contour on sloping sites. The strips vary in width from 3 m to 9 m, depending on the slope.[11] Each strip is planted with a different crop, so that two or three varieties of crop alternate in rows down the hillside. Each strip is harvested individually and subsequently left to fallow or re-planted with a different variety. Popular crop combinations include a low leguminous ground-cover crop in alternation with strips of grain or grass crops.[12] The strip layout improves ease of maintenance while also benefitting from the mix of species.

Relay cropping

Relay cropping is the practice of growing a short-duration secondary crop before or after the regular growth period of a principal (usually cereal) crop on the same field. If rainfall is sufficient to support two crops in sequence, relay cropping can provide a boost to yields and make good use of available stored water before the onset of the dry season. In trials in semi-arid Zimbabwe for example, relay cropping of maize and sunflower has been successful in providing added farm income within available soil water resources.[14]

Encouraging the Natural Adaptation of Plants to Dry Conditions

The physical form and function of a crop plant will depend heavily on how it is tended, trained and watered during development. The following practices are used to influence the development of crop plants in a way that promotes tolerance to dry soil conditions.

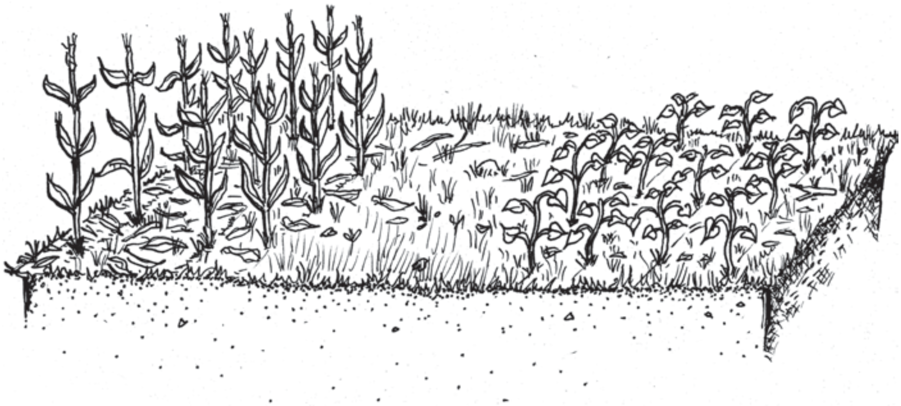

Fig. 8.1. Strip cropping.[13]

Early sowing

Sowing at the very beginning of the rainy season allows the farmer to take advantage of early rains. Plants that are sowed early will develop deeper and more vigorous roots, allowing them to withstand dry periods better than their late-sowed counterparts. They will also form leaf canopy earlier, which shades the soil and reduces evaporation loss. Trials with early sowing of traditional crops in the West Asia/North Africa region have shown impressive yield improvements with this practice.[15]

However, early sowing carries a certain degree of risk, as it is dependent on accurate weather forecasting. To reduce this risk, land can be irrigated once prior to sowing (see supplemental irrigation, Chapter 11), or soil directly under seeding lines can be turned locally to expose the seed to wetter layers of soil (see *planting holes*, Chapter 9).[16] Staggered planting also reduces the risk associated with unpredictable rains.

Sowing should be timed so that the crop's most water-intensive growth stages (usually flowering and grain filling) will not coincide with intra-seasonal dry periods.

Promoting the development of root systems

Farmers should be very familiar with the root shape and spread of their chosen crop(s) (Fig. 8.2). A plant's root system can say a lot about its health, so examining crop roots in successive seasons is very informative – this can also be an easy way to monitor the progress of newly implemented soil and water management practices.

Healthy root systems that develop both laterally and deep into the soil will provide maximum drought tolerance. Depending on the shape and spread of the crop's roots, various management practices can be used to support root

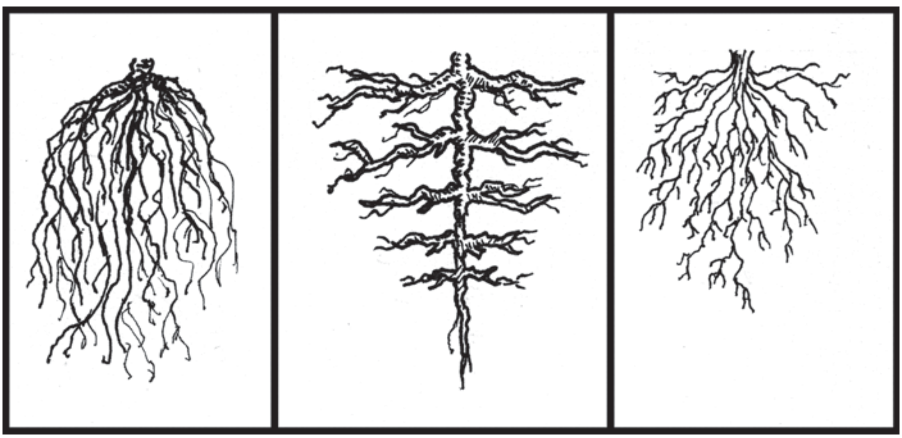

Fig. 8.2. Know your roots.

spread into the soil layers where water is most available. Root system development can be encouraged by:

- Increasing the soil volume accessible to roots. Deep tillage to break up hardpans can make a big difference to the health of the root system. Adequate plant spacing is also important – if crop roots are heavily intertwined, leaving more space between seeds or crop rows will help roots develop laterally and access more soil water.
- Promoting root density in soil layers that don't tend to dry out quickly due to evaporation or deep percolation. Selective (localized) deep tilling can improve root density in lower soil layers where water content is the most stable. Integration of organic matter into the soil layers surrounding the root zone also promotes root density because it provides critical pore space and promotes the activity of soil organisms, which will help retain soil water.
- Accelerating uptake of water by the roots in upper soil layers that are susceptible to rapid drying. In the surface layer, mulching or adding organic matter can improve the ability of shallow roots to absorb water quickly. Fallow periods also improve the water holding capacity of the top layers of soil in preparation for planting.
- Applying water directly to seeds during the early growing stages allows for the formation of healthy root systems early in the plant's life. Planting in furrows or seed pits that will be able to collect water from early rainfall will help the plant develop healthy roots early in life.

Deficit irrigation

Plants have natural physiological adaptation mechanisms that help them to mitigate the effects of water stress and maintain adequate plant water status under less than ideal circumstances. For instance, under low-water situations a leafy plant may tend to drop leaves in order to reduce the cell surface area requiring support, and instead develop new, thinner leaves without sacrificing overall leaf mass. A plant may also undergo *osmotic adjustment* in response to stress, wherein plant cells increase their solute concentrations in an effort to maintain turgor pressure with less water.[17] The same process is observed in plants grown under saline water conditions.

In areas where water supply is limiting, these innate plant adaptations to water stress can be manipulated to provide good crop yields with less water. *Deficit irrigation* is an irrigation pattern based on the selective application of water stress conditions at different stages of plant development. The goal is to make use of the plant's own adaptation mechanisms in order to produce the maximum amount of crop benefit from within a limited supply of water.

The science of deficit irrigation has been developed over years of research investigating the specific effects of water stress on different crops at different growth stages. The result is a detailed set of recommendations for selective irrigation patterns that allow farmers to maximize economic yield within the constraints of limited available water supplies. More about deficit irrigation can be found in Chapter 11.

References

[1] Adapted with permission from Brouwer, C. & Heibloem, M., 1986. *Irrigation Water Management: Irrigation Water Needs*. Training Manual. Rome: FAO. Available at: ftp://193.43.36.92/agl/AGLW/fwm/Manual3.pdf [Accessed February 15, 2015].

[2] Kijne, J.W. *et al*., 2003. *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. Wallingford, UK: CABI, p. 114.

[3] Evenson R.E. & Gollin, D., 2003. Assessing the impact of the green revolution, 1960 to 2000. *Science*, 300, pp. 758–762.

[4] International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), 2008. Agriculture at a Crossroads: Sub-Saharan Africa (SSA) Report, B. McIntyre *et al*., eds. Washington, DC: Island Press, p. 20.

[5] Rosegrant, M.W. *et al*., 2002. *The Role of Rainfed Agriculture in the Future of Global Food Production*. Washington, DC: International Food Policy Research Institute, p. 48.

[6] IAASTD, 2008. Agriculture at a Crossroads: Sub-Saharan Africa (SSA) Report, B. McIntyre *et al*., eds. Washington, DC: Island Press, p. 112.

[7] International Fund for Agricultural Development (IFAD) & United Nations Environment Programme (UNEP), 2013. *Smallholders, Food Security and the Environment*. Rome: IFAD, p. 17.

[8] Koohafkan, P. & Stewart, B.A., 2008. *Water and Cereals in Drylands*. London: Routledge.

[9] Rockström, J. *et al*., 2003. Water productivity in rain-fed agriculture: challenges and opportunities for smallholder farmers in drought-prone tropical agroecosystems, in *Water Productivity in Agriculture*. Wallingford, UK: CABI, p. 158.

[10] Van Duivenbooden, N. *et al*., 2000. Cropping systems and crop complementarity in dryland agriculture to increase soil water use efficiency: a review. *Netherlands Journal of Agricultural Science*, 48, 213–236.

[11] African Conservation Tillage Network (ACT) & International Institute of Rural Reconstruction (IIRR), 2005. Crops and cropping systems, in *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa*. Nairobi: IIRR, p. 105.

[12] Anschütz, J. *et al*., 2003. *Water Harvesting and Soil Moisture Retention*, M. Nederlof & J. Anschütz, eds. Wageningen, The Netherlands: Agromisa Foundation, p. 65.

[13] Adapted from Ibid. p. 64.

[14] Nyakatawa, E.Z. & Nyati, C.T., 1998. Yields of maize and sunflower in relation to sowing time and rainfall distribution under three cropping systems in a semi-arid region in Zimbabwe. *Tropical Agriculture*, 75, p. 428.

[15] Van Duivenbooden, N. *et al*., 2000. Cropping systems and crop complementarity in dryland agriculture to increase soil water use efficiency: a review. *Netherlands Journal of Agricultural Science*, 48, p. 12.

[16] Wani, S.P. *et al*., 2009. *Rainfed Agriculture: Unlocking the Potential*. Wallingford, UK: CABI, p. 186.

[17] Ali, M.H., 2010. Plant: a machinery of water absorption, in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, p. 262.

9 Conservation Agriculture

'Conservation agriculture', also known as 'conservation farming' or 'no-till farming', is a farming style that bucks against long-held understandings of the importance of tillage for land preparation. Conservation farming is an integrated set of practices that seeks instead to minimize soil disturbance, while promoting the continuous recycling of organic matter and nutrients through the plant–soil system. When effectively adopted, these practices have the potential to increase crop yields with respect to conventional farming, all while requiring less work.[1] By supporting the natural cycles of soil regeneration in parallel with crop production, conservation agriculture also promotes the long-term health of the farm ecosystem. It is promoted as a form of *sustainable land management*.[2]

Conservation agriculture (commonly abbreviated as CA) has expanded rapidly over the past 20–30 years, with the strongest growth in Brazil and throughout South America.[3] It is practiced across humid, sub-humid, and semi-arid climate zones. Though still relatively uncommon in sub-Saharan Africa, some countries in the dry tropics of East and Southern Africa have seen an expansion in the number of farms converting to conservation farming over the past two decades.[4] As the benefits of CA become visible, governments, international organizations and farmers' groups are now moving to promote conservation agriculture among poor farmers struggling with poor soil health and excessive erosion.

Conservation agriculture practices are functionally similar to traditional agricultural practices in use before the adoption of the plow.[5] The main obstacle to the adoption of these techniques today is resistance from farmers and extension workers to the principles of minimum tillage, which run in direct opposition to what they have been taught about land preparation.

Conservation agriculture challenges three fundamental principles of conventional farming practice, as outlined in Table 9.1.

Table 9.1. Conventional versus conservation agriculture.

Conventional agriculture principle	Conservation agriculture principle
Tilling is necessary to prepare the soil for planting and to kill weeds.	Tilling should be avoided because it is detrimental to long-term plant health and exposes the soil to erosion.
Crop residues are waste products that should be removed from the field.	Crop residues are valuable and should remain on the field for re-integration into the soil.
Growing wide expanses of a single crop season after season is the most efficient way to farm.	Growing a mix of crops and shifting crops from year to year improves incomes and boosts resistance to pests and disease.

A Different Approach to Soil Management

Readers of this book may have already remarked that effective water management in agriculture is, at its most basic level, contingent on the maintenance of healthy soil. In both dry and wet climates, soil conditions will shape the degree to which water becomes available for plant development throughout the growing season. Good-quality soil is rich in nutrients and organic matter, has a diversity of pore and particle sizes, and sustains a healthy population of worms, insects and microorganisms that improve soil structure, recycle nutrients, and help ward off disease.

So-called 'conventional' tillage-based agriculture does little to promote the long-term health of the soil. In fact, it can damage soil quality by depleting organic matter, reducing water holding capacity, disturbing the habitat of microorganisms, and leaving the land vulnerable to erosion. These effects are part of the reason that agricultural lands are being degraded at such an alarming rate, as introduced in Chapter 2.

Conservation farming is an approach designed to encourage natural soil regeneration between cropping cycles by minimizing soil disturbance and recycling plant residues. Unlike conventional agriculture, where nutrients and organic matter are removed from the soil with each crop cycle, conservation agriculture is based on a principle of minimal disturbance, which reinforces the soil's inherent recycling mechanisms for nutrient and organic matter regeneration (Fig. 9.1). It also advocates planting a diversity of crop and cover crop species within and between seasons, unlike the mono-crop model of conventional agriculture. Diversity of species is a key feature of healthy, sustainable farm systems.

Benefits of Conservation Agriculture

The benefits of conservation agriculture can be significant, but may take a few seasons to become evident. In some cases yields can show improvement as early as the first season, but more often the land will require a few years to adapt and regenerate its self-maintaining properties before yield benefits are observed.[6] Without tillage, weed growth can be problematic in the first years of

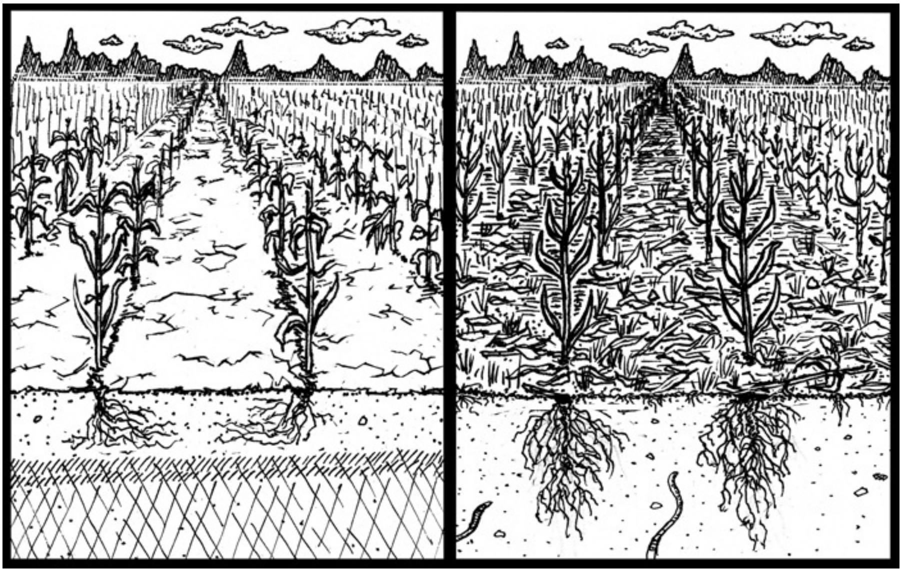

Fig. 9.1 Subsoil conditions under conventional bare-soil tilled agriculture (left) and conservation agriculture (right).

adoption and hand-weeding or herbicide use will be required. However, after a few years the need for weed control should decrease.[7]

Following the conversion to conservation agriculture, soil health should improve year upon year, providing both short-term benefits and improved long-term resilience. The short-term benefits of conservation agriculture include:[8]

- better crop yields;
- reduced cost and labor requirements for land preparation;
- improved soil water holding capacity, and reduced crop water stress during dry spells;
- improved water infiltration into the soil;
- significantly reduced soil erosion;
- reduced water loss to evaporation during the growing season; and
- spaced-out labor requirements that allow farmers and families to prepare land throughout the fallow season instead of all at once at first rains.

Medium- and long-term benefits (5–10 years following conversion) include:[9]

- higher, more stable yields;
- improved soil organic matter content and water holding capacity;
- better soil fertility (and a reduced need for fertilizer);
- reduced need for herbicides and pesticides;
- enhanced microorganism populations providing defense against pests and disease; and
- a reduced risk of crop failure (improved resilience to climate variations).

Yield improvements achieved with conservation farming vary from farm to farm, and are dependent on environmental conditions and the degree to which the practices are implemented. Trials with conservation agriculture undertaken between 1999 and 2003 across semi-arid and sub-humid parts of East Africa showed yield increases of 20–120% compared with conventionally tilled plots.[10] Long-term trials conducted on rainfed wheat and maize farms in central Mexico showed continually higher and more stable yields for both crops with conservation agriculture than with conventional tillage.[11] Lower marginal costs on the conservation agriculture plots also led to significantly higher incomes.[12]

Key Principles of Conservation Agriculture

It is not possible to exhaustively describe the practices of conservation farming within the confines of this book. Indeed, conservation farming is itself the topic of several books (see the further reading box at the end of this chapter for detailed references and freely available conservation agriculture instruction manuals). As a way of introduction, this chapter presents the three fundamental principles of conservation farming and explains why each is important:

1. Reduced or no tillage.
2. Soil cover/crop residue recycling.
3. Diversified cropping.

These principles, and the practices involved in each, should be viewed as an integrated unit to be implemented simultaneously. Conservation agriculture is a systemic practice: each element functions best as part of a whole. Partial adoption of conservation agriculture practices can yield unpredictable results. As an example, reducing tillage without reusing crop residues can actually have a detrimental effect on crop yields.[13]

1. Reduced or no tillage

Conventional agriculture depends on soil preparation using hand hoes, discs, or moldboard plows. This practice is based on the notion that the soil must be turned prior to planting in order to bury weed seedlings and unearth nutrients from deeper layers. While plowing has been common practice for centuries, research conducted within the past few decades has demonstrated that it can significantly degrade soil health. Long-term effects of repeated tillage include:

- formation of a *hardpan* of compact and impermeable soil directly under the plowing depth;
- loosening of the top soil layer, leaving it vulnerable to erosion by wind or water;
- degradation of soil organic matter;
- destruction of subsoil habitat for worms, insects, and microorganisms;

- soil compaction by animals, workers, and machinery; and
- release of organic carbon into the atmosphere as CO_2 (a greenhouse gas that contributes to climate change).

Tillage requires financial investment to buy machinery, and demands that a great deal of labor (both human and animal) be invested in field preparation during the period immediately before planting. Reducing or eliminating tillage greatly reduces these requirements, saving both time and money for the farmer. Financial benefits can however take a few years to be realized, since the full conversion to conservation farming can require additional labor in the early years of adoption. These initial costs have contributed to low adoption rates in some regions.[14] Farmer-to-farmer support networks can be very instrumental in this regard: because land preparation tasks in CA can be performed during the dry season, equipment costs and labor can be spaced out and shared among groups of farmers.

Even in conservation agriculture, some soil loosening is required for seeding, and to break up the hardpan of compacted soil formed over years of repeated plowing. Conservation agriculture recommends alternative, minimum-disturbance field preparation methods for accomplishing these goals without turning the soil. These methods include: (i) deep ripping; (ii) subsoiling; and (iii) direct planting.

Deep ripping

A *ripper* is an attachment that can be fitted to a standard animal or tractor-drawn plow setup (Fig. 9.2). It consists of a thin wedge-shaped metal blade that is drawn through the shallow soil to break up soil crusts or shallow hardpans (less than 10 cm deep).[15] At the same time, ripping creates narrow planting furrows where seeding can be performed. The ripper causes minimal disturbance while still providing loosened soil areas for seed establishment. Rainwater falling between ripped rows will tend to flow into the planted furrows where it is most needed. Ripping is especially useful on light soils with low clay content. Field preparation with a ripper can be performed during the dry season, and is faster than plowing.[16] If ripper attachments are not available on the local market, they can be custom-forged by a blacksmith.[17] *Ripper-planters* are specialized conservation agriculture attachments that perform seeding and fertilizer application in a single pass, drastically reducing labor requirement (Fig. 9.2).

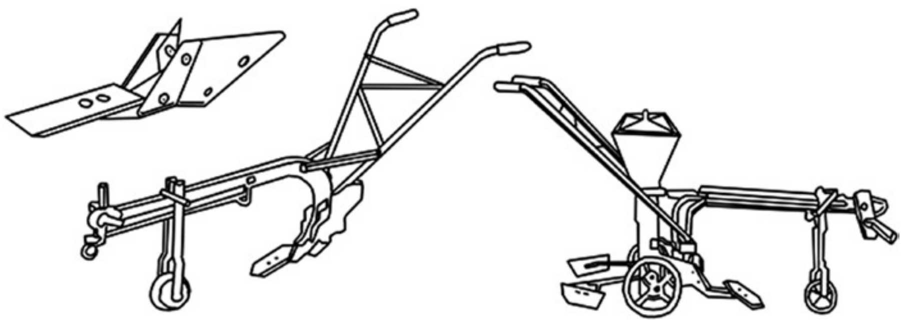

Fig. 9.2. Ripper attachment (Magoye) (left) and ripper-planter (right).[18, 19]

Subsoiling

If the soil is heavy and/or the hardpan is more than 10 cm deep, subsoiling will be used instead of ripping. Like the ripper, a subsoiler is an attachment that can be fitted onto a traditional plow setup (Fig. 9.3). It consists of a long, narrow, sharpened metal rod that is drawn through the soil at a depth of 20–30 cm. This creates a linear fracture in the hardpan where water and plant roots will be able to infiltrate deep into the soil. Because of the need to dig deeper into compacted soils, subsoilers require more power to operate: they are usually pulled by either four oxen or a tractor.[20] (See Box 9.1 for notes on ripping and subsoiling operations.)

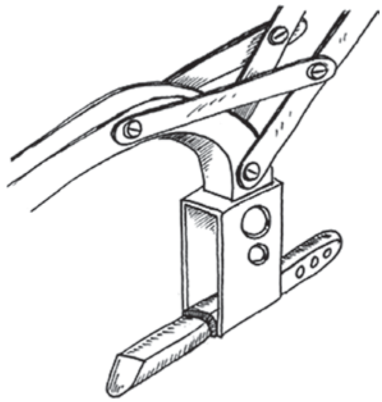

Fig. 9.3. Subsoiler attachment for plow foot.[21]

Box 9.1. Notes on ripping and subsoiling[22]

- Before beginning, dig a few exploration holes into the field to determine if the soil has a hardpan layer, and if so, at what depth. The depth of ripping/subsoiling should be calibrated to run just under the hardpan.
- Ripping and subsoiling are not required every year. Sometimes they are performed only once, or every few years to keep the hardpan from re-forming.
- Both ripping and suboiling should be performed in very dry soil. They can be performed after harvest, before planting, or both.
- On sloped sites, rows should be dug along the contour.
- Rows should be spaced evenly, often 75 cm–1 m apart.

Direct planting

On small fields, or when plowing equipment is not available, land preparation can also be done by hand. *Direct planting* involves digging holes through the hardpan directly underneath crop seeding locations instead of ripping a whole row. The rest of the soil remains undisturbed. *Planting holes* are small pits created using a hoe or pick in the precise area where seeds are to be sown (Fig. 9.4). The holes should be dug just

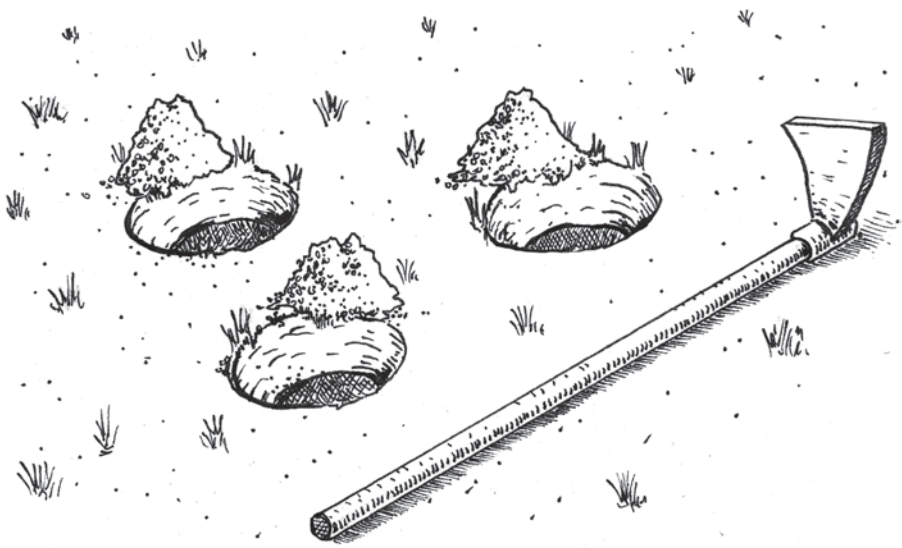

Fig. 9.4. Direct planting in holes.

deeper than the hardpan: it is important to know where this layer lies before beginning the work. Planting holes create vertical channels that allow roots and rainwater to reach down into the subsoil through the compacted soil layer. Creating the holes requires a lot of labor in the first year, but they can be then re-used in subsequent years. Hole locations should be clearly marked so that it is easy to locate them year after year through thick layers of mulch. As with ripping and subsoiling, digging work can be performed during the dry season, resulting in less concentration of labor at the start of the rainy season than with conventional methods. Holes should be carefully and consistently spaced to allow the right distance between plants and among rows. Measured portions of fertilizer, manure or compost, and other amendments can be added directly to the holes before seeding- this saves money and provides favorable growing conditions for the young plant.[23]

Other methods for direct planting involve variations on the planting hole concept. If there is no hardpan or it is very shallow, a sharpened stick (dibble stick) can be used to make shallow holes for seeding.[24] A *jab-planter* is a specialized device used for direct planting in conservation agriculture: it consists of a small seed hopper attached to a simple hand-held tool fitted with a pointed steel end.[25] The farmer jabs the tool into the soil and releases a seed from the hopper in one step.

2. Soil cover/crop residue recycling

In conventional agriculture, farmers commonly collect residues from previous crop cycles and dispose of them, either by burning or as animal feed. These practices remove valuable inputs from the soil ecosystem, robbing it of the nutrients and organic matter necessary for regeneration and sustained fertility over time. When residues are removed, the bared soil is also left vulnerable to erosion. To make matters worse, residual moisture in bare soil is rapidly lost to evaporation, and soil organic matter is quick to break down when fully exposed to the air and the sun.[26] Left uncovered and deprived of organic matter, even rich soil eventually becomes parched and infertile.

Soil cover is a key component of conservation agriculture, and crop residues are valued as an essential part of the soil system. Following the harvest, leftover residues are left to decay on the field in an even layer. Over time, crop residues build up on the surface: combined with cover crops, these form a dense mulch mat that completely covers the soil. As with conventional mulching, there are many benefits associated with this soil cover:

- it forms a protective physical barrier that protects the soil from erosion.
- it preserves soil moisture by reducing both evaporation and runoff, and by discouraging soil sealing to promote infiltration.
- the residue layer will gradually break down and be re-introduced into the soil, improving organic matter content and fertility.
- it greatly enhances the habitat available for worms, insects and microorganisms that are key to keeping the soil healthy.
- it suppresses weeds by forming a protective barrier that is difficult for young plants to penetrate.

Figure 9.5 shows the different subsoil conditions that can exist under bare and covered soil.

Soil cover is created using living cover (crops and cover crops), crop and non-crop plant residues (as a layer of mulch), or some combination of both.

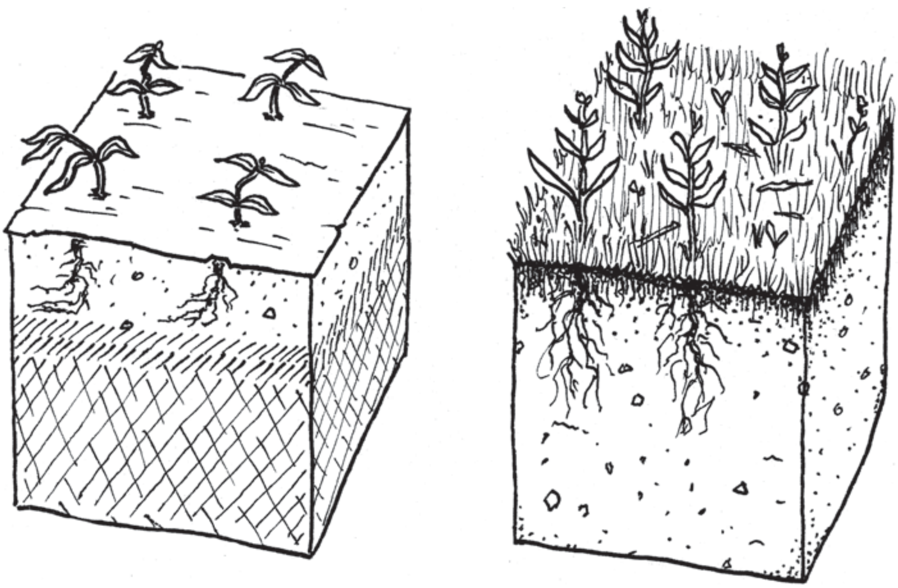

Fig. 9.5. Subsoil conditions under bare soil (left) and effectively covered soil (right).[27]

Cover crops can be planted between rows during the growing season as part of a crop rotation. The residues from mature cover crops are also left on the soil. Other residues, such as tree cuttings, grasses or cover crops cultivated on other parts of the farm can also be brought onto the field to enhance soil cover.

There are a wide variety of combinations used to provide effective soil cover in conservation agriculture systems; the best option for each farm will depend on the materials that are most easily available, and on the moisture and nutrient needs of the primary crop. Once installed, soil cover should not require maintenance, except for filling holes in the mulch layer from time to time. When cover crops are used as soil cover, work is required to prepare the land, plant, weed, and harvest the chosen variety. This effort becomes more worthwhile when cover crops are chosen to provide food or added income.

Farms with livestock will have a more difficult time maintaining good soil cover because animals will wander onto the field to feed on residues. Livestock grazing on the field also causes soil compaction. Whenever possible, conservation agriculture fields should be fenced or otherwise protected to discourage roving livestock. Planting a cover crop that livestock don't like to eat can be an alternative solution.[28]

Some residues are not suitable for building soil cover. Farmers should especially avoid weed plants that have already flowered, or any plant that has been infested with pests or disease. Residues of couchgrass (*Cynodon dactylon*) and *Striga* spp. are to be avoided: these plants are infection agents and should be burned.[29]

3. Diversified cropping

Before plowing became mainstream practice, traditional farming in most cultures involved the simultaneous cultivation (intercropping) of several types of crop on the same field. This was done to take advantage of the synergies between a set of *complementary* crops. Complementary crops are those that enjoy a mutually beneficial relationship, or at least don't directly compete with each other for the same water, sunlight and nutrients. Crops can benefit each other by providing supportive structure, fixing nitrogen, attracting or repelling certain insects, and/or providing shade or ground cover for companion species.

In recent decades, this mixed cropping style has largely been abandoned in favor of *monocropping*, the practice of growing only one crop, re-planted year after year. Monocropping has been endorsed as a more efficient model, and is often promoted alongside mechanization because it simplifies the use of machinery and the application of chemical fertilizers, pesticides, and herbicides.

However, after several decades of experience with widespread monocropping on a global scale, it is now widely recognized that the isolation and repeated cultivation of a single crop is damaging to soil health.[30] Monocropping impacts the health of farms in a variety of ways:

- Growing only one crop year after year strips the soil of certain elements over others, repeatedly mining the soil for those elements without hope for replenishment. This leads to unbalanced, nutrient-poor soil that is difficult to rehabilitate, even with chemical inputs.
- Monocropped plots are inherently vulnerable to pests and disease, which increases the quantity of chemical inputs that are needed to keep them viable.
- Perhaps most importantly, the reduced diversity of species present in wide swathes of monocropped land has compromised the biodiversity of farming regions across the globe. As discussed in Chapter 5, biodiversity is one of the key pillars of sustainable agriculture, and an essential determinant of resilience. Loss of biodiversity from large monocropped farms has negatively impacted the environmental, social, and economic well-being of entire agricultural regions.[31]

Planting a variety of crops in the same soil, either simultaneously or in sequence, reduces the effects of nutrient mining and promotes regeneration between crop cycles. Because different plant species attract different microorganisms, insects and fungi into the soil food web, it also reduces vulnerability to pests and disease.

Crop rotation is a central principle of conservation agriculture. Beneficial secondary crops, especially nitrogen-fixing legumes, play a key role. Crops that can provide good mulch materials are also valuable in a CA rotation: some species are favored for their ability to produce residues of a certain quantity and quality. Intercropping is common, and occasionally two or more different crops are intercropped in one season and rotated in the next. Because the ground does not need to be tilled prior to planting, sequences of intercrops and rotating crops can overlap throughout the year.

Rotations of grain crops and legume ground covers are popular in the semi-arid tropics. When soil water is sufficient, a grain/legume ground cover companion pair is rotated with another pair in 2 or 3 year cycles.[32] Some crop pairs favored by farmers in parts of sub-Saharan Africa include any combination of wheat/sorghum/maize with lablab/cowpea/bean.[33]

Transitioning to Conservation Agriculture

It is essential to properly prepare the terrain before converting to conservation agriculture. Because the soil will no longer be worked year after year, it is important to set the stage for healthy soil development by creating the right conditions for no-till farming to succeed from the outset.

Land preparation steps for the conversion to CA include:[34]

1. Assessing existing erosion or soil degradation problems and addressing them as much as possible. If the land is sloped, terraces or other landforms should be created before converting to conservation farming. If necessary, trees or shrubs can be used to stabilize slopes and provide a diverse soil environment.

2. Breaking up the plowing hardpan in the subsoil (even if not practicing conservation agriculture, breaking up the hardpan will be beneficial). The hardpan can be located by digging a hole 30 cm (1 foot) deep and testing the soil at different depths by jabbing it with a knife or tool (Fig. 9.6). The hardpan will be a layer of compacted earth where the tool cannot pierce easily into the soil – this layer will also resist crumbling. Usually farmers will have some idea where the hardpan is located, since it will be just underneath the regular plowing depth. It is important to recognize how thick the hardened layer is, so that ripping or subsoiling can be calibrated to reach its full depth. The hardpan can be broken up using one of the methods outlined earlier in this chapter.
3. Levelling the field as much as possible and implementing rainwater harvesting strategies as appropriate. The shape of the land will remain unchanged for several years, so it needs to be in the desired shape before conversion.
4. Removing weeds between planting rows, either by pulling them by hand, slashing them with tools, or by applying herbicides. When converting to conservation agriculture, extra effort must be invested to control weeds, which were previously suppressed through tilling. After 2 or 3 years, the natural weed-suppression mechanisms of mulch and cover crops should reduce the effort required for weed control.[35] Conservation agriculture requires regular weeding, so it may be worthwhile to invest in specialized tools or herbicides that help accomplish this job quickly.

The land is now ready to be seeded. Seeding is done using direct seeding, by digging planting holes, or in conjunction with ripping or subsoiling. In the early years, farmers may need to rent or borrow some of the specialized equipment used to accomplish these tasks. Farmers' groups, CA organizations, and NGOs are useful resources that can provide invaluable support to farmers during the transition to conservation agriculture.

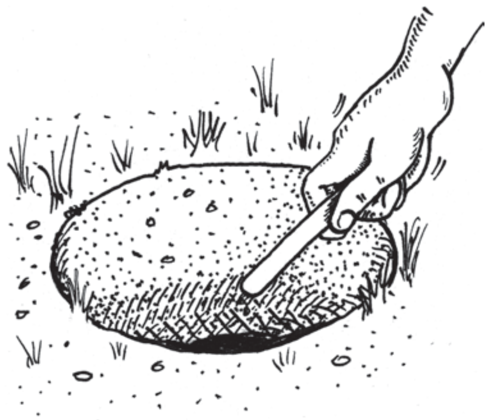

Fig. 9.6. Finding the hardpan.

Further reading – Conservation agriculture

Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa, 2005, a guide produced by the African Conservation Tillage Network (ACT) and the International Institute of Rural Reconstruction (IIRR), Nairobi. Available at: http://www.fao.org/ag/ca/AfricaTrainingManual.html

Visit the Food and Agriculture Organization of the United Nations (FAO)'s conservation agriculture (CA) resources site to find 100+ global and regional resources about CA, available at: www.fao.org/ag/ca/

References

1 Food and Agriculture Organization of the United Nations (FAO) & International Institute of Rural Reconstruction (IIRR), 2012. *Discovery-based Learning in Land and Water Management: A Practical Guide for Farmer Field Schools*. Nairobi: FAO and IIRR.

2 African Conservation Tillage Network (ACT) & IIRR, 2005. What is conservation agriculture?, in *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa*. Nairobi: IIRR, p. 19.

3 Carloni, A., 2001. *Global Farming Systems Study: Challenges and Priorities to 2030*. Rome: FAO, p. 16.

4 ACT & IIRR, 2005. What is conservation agriculture?, in *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa*. Nairobi: IIRR, p. 20.

5 Conservation Farming Unit, 2007. *Conservation Farming and Conservation Agriculture Handbook for Ox Farmers in Agro-ecological Regions I and IIa*. Lusaka: ZNFU House, p. 3.

6 FAO & IIRR, 2012. *Discovery-based Learning in Land and Water Management: A Practical Guide for Farmer Field Schools*. Nairobi: FAO and IIRR.

7 Rockström, J. *et al*., 2007. Managing water in rainfed agriculture, in *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. London: Earthscan, p. 336.

8 Sayre, K. & Govaerts, B., 2011. Use of conservation agriculture to improve farming systems in developing countries, in P. Tow *et al.,* eds, *Rainfed Farming Systems.* Dordrecht, The Netherlands: Springer, p. 864.

9 Ibid.

10 Wani, S.P. *et al*., 2009. *Rainfed Agriculture: Unlocking the Potential*. Wallingford, UK: CABI, p. 22.

11 Sayre, K. & Govaerts, B., 2011. Use of conservation agriculture to improve farming systems in developing countries, in P. Tow *et al*., eds, *Rainfed Farming Systems*. Dordrecht, The Netherlands: Springer, pp. 865–866.

12 Ibid.

13 Ghuman, B., 2001. Tillage and residue management effects on soil properties and yields of rainfed maize and wheat in a subhumid subtropical climate. *Soil and Tillage Research*, 58(1–2), pp. 1–10.

14 Grabowski, P.P. & Kerr, J.M., 2014. Resource constraints and partial adoption of conservation agriculture by hand-hoe farmers in Mozambique. *International Journal of Agricultural Sustainability*, 12(1), pp. 37–53.

15 ACT & IIRR, 2005. Field preparation and planting, in *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa*. Nairobi: IIRR, pp. 35–62.

16 Conservation Farming Unit, 2007. *Conservation Farming and Conservation Agriculture Handbook for Ox Farmers in Agro-ecological Regions I and IIa*. Lusaka: ZNFU House, p. 10.

[17] ACT & IIRR, 2005. Field preparation and planting, in *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa*. Nairobi: IIRR, pp. 35–62.
[18] Duveskog, D. *et al*., 2003. *Soil and Water Conservation with a Focus on Water Harvesting and Soil Moisture Retention*, 1st edn. Harare: FARMESA, p. 86.
[19] ACT & IIRR, 2005. Field preparation and planting, in *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa*. Nairobi: IIRR, pp. 35–62, p. 48.
[20] Ibid. pp. 35–62.
[21] Ibid. p. 40.
[22] Ibid.
[23] Ibid.
[24] ACT & IIRR, 2005. Converting to conservation agriculture, in *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa*. Nairobi: IIRR, pp. 25–34.
[25] Ibid.
[26] Bot, A. & Benites, J., 2005. *The Importance of Soil Organic Matter*. Rome: FAO.
[27] Adapted with permission from FAO & IIRR, 2012. *Discovery-based Learning in Land and Water Management: A Practical Guide for Farmer Field Schools*. Nairobi: FAO and IIRR.
[28] ACT & IIRR, 2005. Soil cover, in *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa*. Nairobi: IIRR, pp. 81–102.
[29] Ibid. p. 99.
[30] Bot, A. & Benites, J., 2005. *The Importance of Soil Organic Matter*. Rome: FAO, p. 18.
[31] International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), 2009. Agriculture at a Crossroads: East and South Asia and the Pacific (ESAP) Report, B. McIntyre *et al*., eds. Washington, DC: Island Press.
[32] ACT & IIRR, 2005. Crops and cropping systems, in *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa*. Nairobi: IIRR, p. 6.
[33] Ibid. pp. 103–114.
[34] ACT & IIRR, 2005. Converting to conservation agriculture, in *Conservation Agriculture: A Manual for Farmers and Extension Workers in Africa*. Nairobi: IIRR, pp. 25–34.
[35] Conservation Farming Unit, 2007. *Conservation Farming and Conservation Agriculture Handbook for Ox Farmers in Agro-ecological Regions I and IIa*. Lusaka: ZNFU House.

Part 3 Irrigation

Preamble to Part 3

What is Irrigation?

Irrigation is the term used to describe any type of water application to agricultural fields that is administered by artificial means (as opposed to natural means such as rain, floods, and runoff). Irrigation exists in many forms, and involves widely varying levels of technology. On small farms in developing countries, irrigation is primarily human-, or animal-powered, and systems are designed around locally available resources. On larger commercial farms, mechanical irrigation is used to reduce the labor required to apply water to large plots. These installations carry a high capital cost but are often more efficient and easier to calibrate than simpler methods.

Full irrigation is the practice of applying water to the field at regular intervals throughout the growing season in order to maintain a desired level of available soil water. *Supplemental irrigation*, as introduced in Chapter 7, is the selective application of water to primarily rainfed fields when rainfall is insufficient to protect the plants against water stress. Application methods for supplemental irrigation are much the same as full irrigation methods, though they generally lie toward the low end of the technology spectrum. On smallholder farms in the semi-arid tropics, supplemental irrigation is usually applied using low-cost surface irrigation.[1] Supplemental irrigation is a useful complement to the soil and water management practices outlined in Part 2, and significant productivity improvements have been observed in cases where these strategies are implemented together.[2] Because water is only applied when needed, the efficiency of crop water use under supplemental irrigation is much higher than it is for fully irrigated crops.[3]

History and Current Thinking

In the latter decades of the 20th century, irrigation development was promoted widely by some international organizations as a promising strategy for alleviating poverty by improving crop yields. Large-scale irrigation projects proliferated in the 1970s and 1980s, with the greatest expansion occurring in the countries of East and South Asia. While these developments have been credited with lifting millions of people out of poverty, we are now seeing the negative effects that irrigation mega-projects have had on water supplies and livelihoods in those areas.[4] In many countries, soil salinization, dropping water tables, dried-up rivers and groundwater contamination now threaten the livelihoods of the very farmers who were the intended beneficiaries of new irrigation systems.[5,6] Large irrigation projects have also sparked conflict among water users and created antagonistic relationships among districts within shared watersheds.[7] Today, a renewed emphasis on the virtue of smaller, single-farm or community-level water management projects is found in the literature of organizations like the FAO and the Consultative Group for International Agricultural Research (CGIAR).[8] Because it provides more efficient use of valuable blue water reserves and requires less investment at all levels, supplemental irrigation is a promising alternative to full irrigation in resource-poor areas.[9]

Dangers of Large-scale Irrigation

The yield potential of irrigated farms is impressive, and more water application in agriculture will help to produce more food. However, irrigation development can have consequences for both the natural environment and human health in the longer term. These must be considered before moving towards irrigation at a large scale.

Some negative effects that have been associated with long-term irrigation include:

- Environmental damage:
  - Waterlogging and salinization – These related phenomena are discussed in Chapter 2, and are a major threat to agricultural land worldwide.
  - Soil compaction and nutrient leaching.
  - Creation of favorable environments for the formation of plant diseases and pests- especially problematic are fungal diseases including root rot (*Phytophthora* spp.), weeds, and insects.
  - Erosion – Soil erosion is especially rampant in poorly constructed surface irrigation networks.
  - Pollution – Contamination of surface- and groundwater with agricultural chemicals has significantly damaged the health of water environments

worldwide. Agricultural runoff also causes oxygen-deprived dead zones in water bodies, threatening aquatic species.
  - Ecosystem damage from dam construction – Communal irrigation projects are often accompanied by investment in water storage structures, usually dams, which have their own set of environmental impacts. Dam construction requires major disruption of natural water courses, with repercussions for both natural ecosystems and human settlements.
- Human health hazards:
  - Contamination of drinking water wells with harmful substances – Specific problems include pesticides, which can be toxic to humans, and excess nitrate from fertilizers, which can cause methemoglobinemia, known as 'blue baby syndrome'.[11]
  - Creation of habitat for disease agents – Water pooling on land surfaces can lead to the proliferation of serious diseases including malaria, yellow fever, dengue fever, and schistosomiasis.[12] When wastewater is used in irrigation, dangers also include cholera, typhoid, ascariasis, amoebiasis, giardiasis, and *Escherichia coli*.[13] Risks are highest where water is allowed to stagnate.
- Socio-economic effects:
  - Inequality of access – The development of district-level irrigation networks can cause increased inequity among landholders, water-rights' holders and farm workers, and cause population migrations that have a negative effect on social structure.[14]
  - Over-extraction of surface or groundwater reserves – Large-scale irrigation projects contribute to the over-exploitation of precious blue water reserves, often with serious social and environmental consequences. Irrigation withdrawals have been blamed for the drying of several major water bodies worldwide over the last 40 years.[15] Some notable victims of over-extraction for irrigation include Lake Chad, the Aral Sea and the Colorado River.

These long-term effects must be balanced against the real potential for yield increases provided by irrigation development. The focus of this book is predominantly rainfed farms that may use supplemental irrigation to improve soil moisture during dry periods. When water is applied judiciously and according to need, the harmful impacts of irrigation are significantly reduced. In regions with shallow water tables or poorly drained soils, water application can also be balanced by artificial drainage in order to reduce the problems associated with salinization, waterlogging, and disease.

In order to be sustainable, irrigation choices must be scaled to ensure that they do not impact the long-term viability of water sources, the local environment, and the soil. These three natural features form the foundation of every agricultural enterprise, and projects that damage this foundation will ultimately not succeed.

Topics Covered in Part 3

Part 3 provides detailed information about irrigation methods commonly used on small farms (Chapter 10). It also explains briefly how to determine irrigation water requirement and schedule water applications, and provides an introduction to both deficit irrigation and artificial drainage (Chapter 11). The last chapter includes important information about the quality and expected quantity of water sources for irrigation, and outlines some common low-tech water-lifting devices used in transporting water to the field (Chapter 12).

References

[1] Wani, S.P. *et al*., 2009. *Rainfed Agriculture: Unlocking the Potential*. Wallingford, UK: CABI, p. 203.

[2] Oweis, T., 1997. *Supplemental Irrigation*. Aleppo, Syria: International Center for Agricultural Research in the Dry Areas (ICARDA).

[3] Ibid. p. 9.

[4] Farurès, J.-M. *et al*., 2007. Reinventing irrigation, in *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. London: Earthscan, p. 358.

[5] Shah, T. *et al*., 2012. *The Global Groundwater Situation: Overview of Opportunities and Challenges*. Colombo: International Water Management Institute, pp. 1–2.

[6] Couture, J., 1999. *Desk Study on Irrigation and Water Management in Sub-Saharan Africa and the Caribbean*. Wageningen, The Netherlands: CTA Technical Centre for Agricultural and Rural Development.

[7] Ibid.

[8] Some examples include: (i) Food and Agriculture Organization of the United Nations (FAO), 2014. *The State of Food and Agriculture: Innovation in Family Farming*. Rome: FAO; and (ii) Consultative Group for International Agricultural Research (CGIAR) Consortium, 2012. *Sustainable Agricultural Productivity Growth and Bridging the Gap for Small-Family Farms: Interagency Report to the Mexican G20 Presidency*. Montpellier, France: CGIAR Consortium.

[9] Oweis, T., 1997. *Supplemental Irrigation*. Aleppo, Syria: ICARDA.

[10] Ali, M.H., 2011. Water conveyance loss and designing a conveyance system, in *Practices of Irrigation & On-farm Water Management,* Volume 2. New York: Springer, p. 12.

[11] Ali, M.H., 2011. Pollution of water resources from agricultural fields and its control, in *Practices of Irrigation & On-farm Water Management,* Volume 2. New York: Springer, p. 248.

[12] Stockle, C.O., 2001. *Environmental Impact of Irrigation: a Review*. Pullman, Washington: State of Washington Water Research Center, p. 10.

[13] Ibid.

[14] Couture, J., 1999. *Desk Study on Irrigation and Water Management in Sub-Saharan Africa and the Caribbean*. Wageningen, The Netherlands: CTA Technical Centre for Agricultural and Rural Development.

[15] Postel, S.L., 2003. Securing water for people, crops, and ecosystems: new mindset and new priorities. *Natural Resources Forum*, 27(2), pp. 89–98.

10 Irrigation

Irrigation Decisions

There are many ways to apply irrigation water. Several factors must be considered when choosing *if*, *how*, and *how much* to irrigate. The choice of irrigation system will depend on:

- The type of blue water source(s) accessible – How close is the blue water source to the field, and how will it be moved? Is it groundwater, surface water, captured rainwater, or another source? What quantity is available for sustainable use? Make no assumptions about the abundance of a water source: it is important to thoroughly assess the supply and consult with other users in the watershed before installing an irrigation scheme.
- Quality of the water source(s) – What water quality is available? Low-quality or sediment-rich water will clog pipes and pumps, so it is not suitable for certain irrigation systems. Saline water needs to be managed using specific techniques. Water quality is discussed further in Chapter 12.
- The energy source that will be used to move water – If there is a sufficient difference in elevation between the water source and the field, irrigation can be powered by gravity. Otherwise, some form of energy input will be required to move water from the source to the field, and to distribute it over the cultivated area. This could be human or animal power, or energy from fuel combustion in the case of mechanical pumps.
- Availability of labor – Some irrigation methods will require more labor than others for installation, operation, and maintenance.
- Soil type – As covered in Parts 1 and 2, soils differ widely in their ability to infiltrate and store water. Some irrigation methods are best suited to certain types of soils. As an example, furrow irrigation methods work poorly in fast-draining sandy soils because water added to these soil types tends to

drain vertically downward instead of moving laterally though the soil profile from the furrow bottom toward plant roots.
- Crop type – Expensive irrigation methods are best suited to high-value crops. Some crops tolerate being in moist soil for extended periods, a common condition in some flood irrigation methods. Others are sensitive to such high-water conditions, and require more gradual wetting.
- Climate – Climate is an important determinant of the efficiency of an irrigation system. For example, sprinkler irrigation can be very inefficient in dry, hot climates, because much of the sprayed water will be lost to evaporation.
- Local experience – What irrigation methods are nearby farmers using? It will be more difficult to install an irrigation method that has not already been tried within the local farming community. Imported systems often require materials and replacement parts that can be hard to find in the local marketplace.
- Availability of investment – Some irrigation systems are expensive to install and maintain, and this investment may take a long time to recoup in added revenue from irrigated crops. It is important to consider not just start-up costs for materials and construction of the system, but also ongoing operating costs, repairs, and the replacement costs of system components. The cost–benefit ratio of a new irrigation system should be explored before investing.

Water Application Methods

Gravity-fed irrigation methods

In this category of irrigation systems, water distribution and application processes are powered exclusively by gravity (though in some cases pumping is still used to move water to the field or into storage). This category includes various forms of *surface irrigation* and *micro-irrigation*. Gravity-fed irrigation methods are typically less costly to install and operate than pressurized methods.

Surface irrigation

Surface irrigation networks are powered by the movement of water from a high point toward fields that sit at lower elevation. The flow of water is directed through a network of gullies and trenches designed to direct and infiltrate water toward the plant root zone. Careful land leveling is critical in surface irrigation networks.

Surface irrigation involves a full or partial flooding of the field surface, followed by slow drying over the course of a few days or more. This rhythm of near-saturation conditions followed by gradual drying creates only brief windows of well-balanced soil moisture in between wet and dry conditions. This pattern is therefore not optimal for plant health, which prefers a constantly moist, yet aerated, soil environment.[1] Land flooding techniques also have low efficiency because they are subject to considerable water loss through the combined effects of evaporation, runoff, and seepage. When open, unlined channels are used to convey water, upwards of 10–35% of the water flow will be lost to seepage and evaporation during conveyance.[2] Surface irrigation is difficult to combine with mulching and crop residue recycling practices advocated in Part 2. Despite these drawbacks, surface irrigation is the method most commonly used by poor farmers with access to irrigation water, due to its simplicity and low cost.[3]

BASIN IRRIGATION. (also called check basin irrigation, level-basin irrigation, check flooding, dead-level irrigation)

Basin irrigation is perhaps the simplest form of surface irrigation. It involves the construction of a series of level basins at the base of crop plants, where water is encouraged to accumulate and infiltrate slowly into the ground. The basins are filled during irrigation events when water is released from a high point and allowed to spread through the field through a carefully levelled network of channels, dykes, and berms. Distributed water is kept in place by low bunds that surround the basin areas. These *check bunds* can be permanent, semi-permanent, or seasonal.[4]

Basins range from very small, at the scale of individual plants or trees, to very large, at the scale of entire rice paddies several acres in area. Basins need to be kept as level as possible, and can be square, rounded, or aligned across the contour. Some basin systems (including paddy rice systems) are sequential, where a first basin is filled and allowed to spill over into the next, and so forth over several basins. Basin systems can be constructed by hand or using animal traction, and are easy to operate and maintain. The system can be relatively efficient if basins are well maintained, but they tend to require a large stream or reservoir size in order to function well.[5] Table 10.1 provides some details about basin irrigation, and Fig. 10.1 shows a simplified basin layout.

Table 10.1. Basin irrigation.[6]

Used with	Close-growing field crops, maize, sorghum, tree crops, rice paddies, orchards
Favorable conditions	Uniform soils, flat fields with slope under 1%. Plants must be able to tolerate wet conditions. Well-drained soils are preferable. Coarse soils will require small basins, while fine soils can support very large basin sizes. Not suitable in very rainy climates where drainage is poor.
Efficiency	Medium
Advantages	Can rehabilitate saline soils, are easy to operate and maintain, can be constructed by hand or with animal traction, usable on irregular or small fields, adaptable to many plant types, reduce runoff.
Disadvantages	Expensive to construct when a high degree of land leveling is required, channels and basin dykes interfere with farm machinery, may require large flows of water, and will cause waterlogging in high rainfall areas.

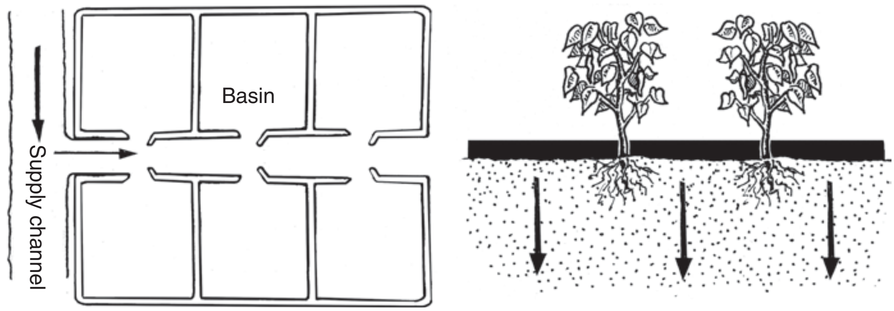

Fig. 10.1. Basin irrigation (left)[7] and soil wetting pattern (right).[8]

FURROW IRRIGATION. Furrows are narrow channels created through the field to simultaneously transport and infiltrate water into the ground between crop rows. Crops are planted on planting ridges between furrows. Water moving through furrows migrates into the plant root zone through lateral infiltration and capillary action. Furrows are usually in the range of 20–30 cm deep (measured from ridge top to furrow bottom) and water levels during irrigation should not exceed two-thirds of this depth.[9] Furrow irrigation is adapted for use with most widely spaced row crops, ranging from trees to root vegetables. The use of furrows for water application avoids waterlogging around plant roots and promotes healthy root development throughout the soil profile of the planted ridges.

Furrows can be short or long, depending on soil type and the precision of the slope applied. Long furrows need to be precisely leveled and are often created by machine.[10] Water should be able to flow quickly all the way to the end of the furrow, wetting the row of plants as evenly as is feasible: furrow slopes generally vary between 0.5% and 1%.[11] Very sandy or clayey soils are not usually appropriate for furrow construction. On sloping fields, furrows can be constructed along contour lines. *Broad-bed and furrow* systems are wider versions of the furrow concept wherein broad, flat-topped beds (150 cm or wider) set between furrows are planted with two or more rows of crops. This system is used in areas with clay soils and intense rainfall.[12] In water-scarce regions, *alternate furrow irrigation* is practiced: water is only applied to every second furrow with each water application, then the irrigated furrows are alternated in the following application.

Furrow irrigation can be very efficient when the furrows are effectively managed, but highly inefficient when management is poor. Poorly managed furrows will not spread water evenly along the planted ridges, resulting in uneven wetting and water wastage. Table 10.2 provides some details about furrow irrigation, and Fig. 10.2 shows a simplified furrow layout.

BORDER IRRIGATION (BORDER STRIP METHOD). Border irrigation is a variation of basin irrigation wherein land is divided into wide, level rectangular strips

Table 10.2. Furrow irrigation.[13]

Used with	Widely spaced row crops, root crops, trees
Favorable conditions	Uniform, loamy soils with good infiltration, where labor and equipment are available for furrow construction and leveling
Efficiency	Low to High, depending on design and management
Advantages	Can work well with saline water sources. Furrows can double as drainage channels in high rainfall areas. Easy to maintain and operate, can be built by hand or with animal traction. Suited to sloping fields, adaptable to many plant types, and less prone runoff and evaporation losses than other surface methods. Usable with a range of stream sizes.
Disadvantages	Construction is labor-intensive. Leveling must be precise on long furrows, which may be difficult to maintain or require skilled labor. Furrows interfere with farm machinery.

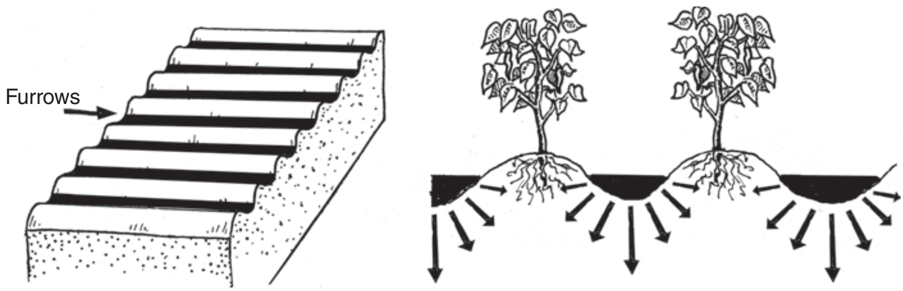

Fig. 10.2. Furrow irrigation (left)[14] and wetting pattern (right)[15].

surrounded by low ridges of earth (borders). Water from an upstream supply channel moves into the strip through openings in the border, and slowly migrates downslope in sheet flow toward the far end of the strip. Border irrigation is most often installed on relatively flat fields where grain or closely spaced forage and legume crops are grown. Land leveling is critical in border strip irrigation so that water spreads evenly. It requires a good rate of flow in the supply channel so that water will spread all the way to the end of the strip, but not so fast as to limit infiltration and produce excessive runoff. Border irrigation is a demanding method that is labor-intensive to build and difficult to implement on uneven soils or on sloping sites.

Border strips can be used on all types of soil, but the length and width of the strip must be adjusted accordingly. Sandy and silty loam soils will require shorter strips, while fine clay-rich soils can support long strips, sometimes hundreds of meters long.[16] Strips can be narrow or very wide, often ranging from 3 m to 15 m in width.[17] Border strips are built with very gentle longitudinal slopes ranging from 0.2% to 0.5%, depending on the infiltration rate of the soil (slopes are shallow in clay soils and steeper in sandy conditions).[18] During water application, flow is cut off shortly before the water sheet reaches the end of the strip to avoid waterlogging the downhill portions. Border irrigation can also be arranged along the contour (called contour border irrigation) on sloping or undulating landscapes. Table 10.3 provides some details about border irrigation, and Fig. 10.3 shows a simplified border irrigation layout.

Table 10.3. Border irrigation.[19, 20]

Used with	Close-growing grain, forage, or legume crops
Favorable conditions	Flat or gently sloping topography, uniform soils of any type. Most suitable when water supply is abundant and/or land area is limiting.
Efficiency	Medium to high
Advantages	Little land is wasted as crops can also be grown on border bunds. Variable stream sizes can be used. Efficiency is good when properly constructed. Easy to construct by hand, with moldboard plow or ridger tool. Drainage is achieved through downstream drainage channels.
Disadvantages	It can be very difficult to achieve even flows through the full length of strips. Leveling must be precise, so initial costs can be high. Water distribution will be uneven if leveling is poor. Requires an even and regular land surface, unusable when soil covers or residues are used. Not suitable on sandy soils with high infiltration rate. In practice, efficiency is often low. Requires high volumes of water.

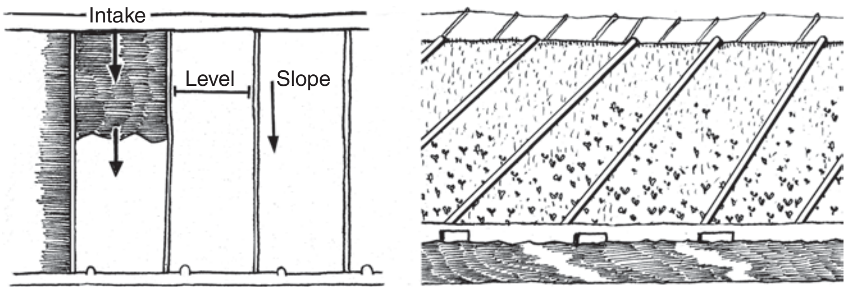

Fig. 10.3. Border irrigation (left) and contour strip irrigation (right).[21]

Micro-irrigation

Micro-irrigation is a general term used to designate small-scale, low-cost irrigation techniques that deliver water more efficiently than traditional methods of hand-watering and surface flooding. Micro-irrigation is especially useful on smallholdings where water availability is limited. The installation of micro-irrigation on small plots and kitchen gardens can yield significant improvements in water productivity, while reducing the labor required to apply water by hand. Experiments with micro-irrigation have shown that these methods can produce higher yields with significantly less water than surface methods.[22]

MICRO-DRIP IRRIGATION. Drip irrigation is a highly efficient water application method which delivers irrigation water directly to the soil around plants drop by drop. Because water is delivered directly to the soil surface and only where it is needed, drip irrigation significantly reduces water losses to evaporation and deep percolation. Pressurized drip irrigation (see next section) is among the most efficient forms of water delivery used in agriculture.[23] However, pressurized drip irrigation networks are expensive to construct and require complex equipment for treating, pumping, and balancing the water flow.

Micro-drip irrigation is a variation on the concept of drip irrigation that uses only gravity pressure to drive water distribution, eliminating the need for sophisticated pumps and plumbing networks. The most basic micro-drip systems can be constructed with simple and easily accessible materials. These so-called 'bucket drip systems' are composed of a large bucket or water reservoir raised on a platform of a few meters in height, connected to a compact system of plastic drip hose that runs through the field between rows of crops. The drip hose line is connected to the reservoir using whatever materials are available to create a good sealed connection. A valve installed on the pipe leaving the reservoir allows for the water feed to be turned on and off as desired. After the drip hose lines are laid in place, small holes are pierced in the hose at the location of each plant stem and emitters are installed. The ends of the hose lengths are sealed – this creates the internal pressure needed to force water out of the emitters when the bucket is full. Emitter holes pierced in the drip hose lines should be small enough that water flows evenly along the length of the pipe, but not so small that they will become blocked by sediment. If the irrigation water available is high in sediment, it is best to install a filter mechanism at the bucket fill point or between the bucket outlet and the irrigation pipe.[24] Kits containing the range of drip irrigation components (sometimes called bucket drip kits) are available for purchase in some countries.[25]

Micro-drip systems have a low initial cost, but some of the smaller plastic components (drip line, emitters, etc.) will need to be replaced every few years. Drip irrigation systems significantly reduce the labor requirement on small plots that were conventionally watered by hand. This can provide significant benefits in terms of free time. They are also well suited to subsistence plots and kitchen gardens.[26]

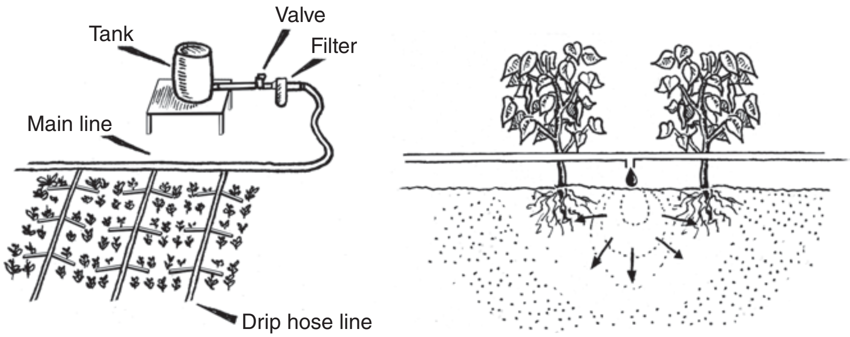

Fig. 10.4. Micro-drip irrigation (left)[27] and wetting pattern (right)[28].

POROUS POT OR POROUS PIPE IRRIGATION. These micro-irrigation methods take advantage of the porous properties of clay (ceramic). When their surroundings are drier than their contents, clay receptacles gradually seep water through tiny pores in their walls. By applying irrigation water through a clay container buried in the soil, it becomes possible to apply water directly to the root zone slowly and according to need. This extends the period of wet soil after an irrigation event and creates a favorable, consistent moisture environment for nearby plant roots. The controlled dosage of water also helps to starve out weeds. These systems are highly efficient and produce good crop yields with a fraction of the water (80–95% less in some cases) required for surface irrigation.[29,30]

Because clay is relatively fragile, these methods are not usable in cold climates or in shifting soils. They are most commonly used with vegetable plots and in orchards, though at maturity the deep and vigorous roots of some woody trees or bushes can pierce through the clay looking for water. Sediment-free water should be used because small particles can block clay pores and shorten the lifespan of the system.

Porous pot irrigation (also known as porous cup, clay pitcher, or clay pot irrigation) is a simple hand-watering technique that has been practiced for thousands of years.[31] Instead of applying water to the soil directly, irrigation water is poured (by hand or with a hose) into a clay pot buried in the ground close to the base of crop plants. The gradual release of water from the pot allows farmers to extend the period between waterings, and the targeted application of moisture according to the relative dryness of the soil helps to maintain healthy subsurface conditions and good soil structure. This technique also greatly reduces water loss to evaporation, runoff and deep percolation.

Porous pipe irrigation is a variation on the porous pot method which replaces the pot with clay pipe(s) buried along a row of crops. Water poured into the pipe will seep out toward the plant root zone through clay pores and pipe joints. The pipe sections used are typically around 25–30 cm in length and 7.5 cm in diameter.[32] Pipe sections can be manufactured by local potters, or made by farmers themselves if appropriate firing equipment is available.[33] During assembly, several pipe sections are joined together using standard cement to form a pipe length corresponding to a row of crops. They can also be buried unjointed to increase the rate of water release.[34] One end of the pipe is sealed, and the other is fitted with a vertical pipe section which will be used for filling. The pipe length is buried alongside a row of plants, or between two rows, at a depth and distance determined according to soil type and the plant's lateral root spread. The pipe should be laid flat or at a gentle slope no greater than 1%. Table 10.4 provides some details about the various forms of micro-irrigation, and Fig. 10.5 shows a schematic layout of the porous pipe and porous pot methods.

Table 10.4. Micro-irrigation: micro-drip, porous pot and pipe.[35]

Used with	Vegetable gardens, field crops or trees. Often used with kitchen gardens.
Favorable conditions	Flat or gently sloping topography. Fine-textured soils are preferable but also effective on sandy soils. Primarily used for irrigating small plots.
Efficiency	High to very high
Advantages	Very water efficient, low-cost strategies. No skilled labor is required for irrigating. Waterlogging is avoided and good soil moisture conditions are sustained for several days after irrigating. Irrigation frequency is reduced. Significant water and labor savings are possible and water productivity can be enhanced over surface or hand irrigation techniques.
Disadvantages	Water distribution can be uneven if systems are not carefully designed. Regular maintenance is required to ensure proper functioning of drip lines or pipe sections. High labor demand, especially for porous pot and pipe systems. Some components may need to be repaired or replaced every few years. Micro-drip lines can interfere with farm machinery. High-quality water needed unless filtration is provided.

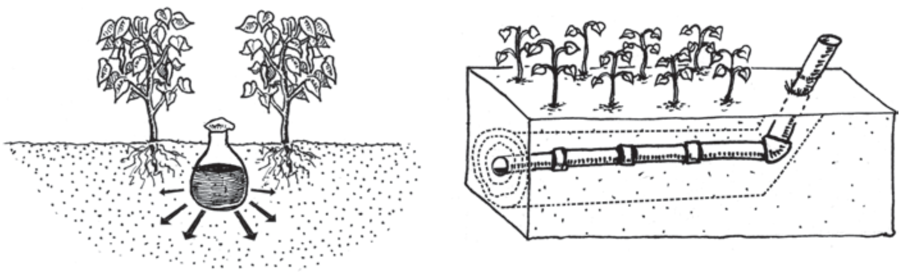

Fig. 10.5. Porous pot (left) and porous pipe (right) irrigation.[36]

Pressurized irrigation methods

This category spans numerous configurations of sprinkler and drip irrigation. In general, pressurized irrigation methods require a great deal more equipment, energy and investment than their gravity-fed counterparts. However, these methods tend to offer superior operational conditions, providing farmers with better control over the timing, rate, and distribution of water applications.[37] In addition, sprinkler and drip irrigation allow for gradual and carefully calibrated soil wetting than surface irrigation, providing more favorable soil moisture conditions.

Sprinkler irrigation

Sprinkler is the most common form of irrigation in the pressurized category. Sprinkler irrigation is practiced across the globe, often on large commercial farms with high production output. This method is preferred by commercial farmers because it allows for the uniform distribution of a precise depth of water, calculated according to soil water depletion. Sprinkler irrigation is also more adaptable than surface irrigation in that it can be used on difficult sites characterized by irregular topography or uneven soils that are too shallow or sandy to irrigate with other methods.[38] Sprinkler methods are expensive to build and maintain, but can provide good water use efficiency and high yields when properly designed and operated.

There are many types of sprinkler irrigation, classified according to the shape of the spray and the way the system is laid out to cover the land surface. All sprinkler systems include three basic elements: (i) a pumping unit; (ii) a network of pipes; and (iii) spray nozzles (sprinklers) that send water out over the field.[39] In a typical irrigation network, *mains* pipes lead water from pumps into the *submains*, which in turn distribute water among the *laterals* that are located directly on the field and house the spray nozzles. The nozzles are connected to laterals by means of *pipe risers*, which raise them to the desired height. Pipe risers are calibrated to deliver water just above the height of the crop, so that leaves and stems are wetted during irrigation, providing a cooling effect.

Spray nozzles (commonly called sprinklers) of sprinkler systems are arranged to provide complete and even coverage of the field (so-called 'head-to-head' coverage). Water efficiency is enhanced by minimizing the overlap between the coverage areas of each nozzle. Nozzles can be fixed or rotating, and flow rates are regulated by valves and staggered pipe diameters calibrated to provide even coverage throughout the network.

Sprinkler systems can be either permanent or portable. *Portable sprinkler systems* are the most common pressurized system used on small farms. The entire network of a portable system can be lifted and moved to irrigate different parts of the field. These systems can also be moved from one water source to another as needed, which can facilitate irrigation in a context where water sources may be inconsistent. These units are typically the cheapest and easiest to maintain, but the labor required to operate them is considerably higher than for permanent sprinkler systems.[40] Because they are so often manipulated, portable systems can also require frequent maintenance. Table 10.5 provides some details about sprinkler irrigation, and Fig. 10.6 shows a schematic layout of the system's components.

Table 10.5. Sprinkler systems.[42]

Used with	All kinds of crop, pasture, and orchards
Favorable conditions	All kinds of topography can be used on sites that are undulating and/or difficult to level. Unlike surface irrigation, these are suitable for light, sandy soils. Can be used on variable or shallow soils.
Efficiency	High, except in hot or windy climates where evaporation and drift cause water loss.
Advantages	Usable on all kinds of field and crop. Water applications can be carefully calibrated. Can be adapted to apply fertilizer or chemicals along with water. Low labor requirement compared with surface methods. Losses to deep percolation and runoff can be avoided. Efficient where water supplies are scarce. Occupies little space.

Continued

Table 10.5. Continued.

Disadvantages	Water distribution can be uneven if the system is not well designed. Regular maintenance is required to ensure proper functioning. High energy requirement and capital cost. Requires clean or filtered water, otherwise nozzles can clog. May require skilled operators. Can contribute to the salinization of soils.

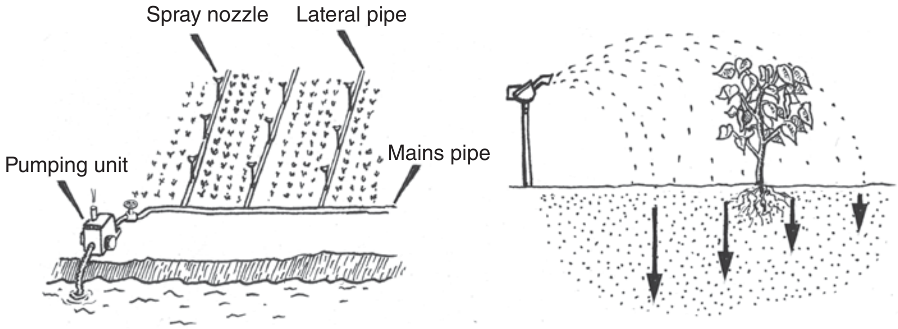

Fig. 10.6. Sprinkler system components (left) and wetting pattern (right).[43]

Drip irrigation

Just like micro-drip irrigation, pressurized drip irrigation is based on the installation of long lengths of plastic pipe along crop rows. Water is allowed to escape through emitters inserted into the plastic pipe at intervals roughly corresponding to plant spacing. Sometimes called '*trickle irrigation*', pressurized drip irrigation is a highly efficient water delivery method. Because the area of soil wetted by drip systems is limited to the area around the plant's roots, evaporation is minimized and weed growth is discouraged. Water applications can be calibrated to provide each plant with its precise daily water requirement, so deep percolation losses can also be avoided. In addition to limiting water losses, the small and frequent wetting rhythm possible with drip irrigation provides an excellent balance of moisture and aeration, creating an optimal environment for plant growth.[44]

Drip irrigation systems can be especially beneficial in arid areas with dry soils and limited water availability. This method is also the safest way to apply saline or poor-quality water, though sediment-rich water will require reliable filtration.[45]

Drip systems are composed of three elements: (i) the pump unit; (ii) the mains feed line and associated submains; and (iii) the drip lines fitted with emitters.[46] Usually, the pump unit incorporates a filtration system to reduce the clogging of drip emitters by sediment or bacteria in the water. Fertilizer tanks can also be incorporated at this stage to enable *fertigation* (dissolved fertilizer application with irrigation water). Drip lines are usually flexible PVC pipe lengths that are no more than 50 m long.[47] Submains are fitted with pressure valves that regulate the flow to ensure that water will be applied evenly along the length of the drip line. Emitters are chosen based on water characteristics (to minimize clogging) and spaced according to the cropping layout.

Pressurized drip irrigation is the most precise and efficient irrigation method currently available, and also among the most expensive. It is typically used on small fields or orchards producing high-value crops. Nonetheless, water savings are considerable: savings of over 80% have been recorded as compared with furrow irrigation.[48] Table 10.6 provides some details about pressurized drip irrigation, and Fig. 10.7 shows a schematic layout of the system's components.

Table 10.6. Drip irrigation.[49]

Used with	Fruit and vegetable crops, high-density orchards, tree crops. Often used on small plots of high-value crops
Favorable conditions	Flat or gently sloping topography. All types of soil. Cooler climates reduce wear and tear on plastic pipes, which can be problematic in drip systems.
Efficiency	Very high
Advantages	Very water efficient. Suitable for areas with limited water supplies. Water applications can be carefully calibrated. Easy to achieve optimal water and aeration conditions, increasing yields and improving water productivity. Irrigation can be fully automated. Little labor requirement.
Disadvantages	High capital investment and technological complexity. Clean water or filtration unit is required to avoid clogging drip lines. Regular maintenance is required to ensure proper functioning. Skilled labor may be required for some maintenance tasks. Some components may need to be repaired or replaced every few years. Plastic pipes are subject to UV damage. Can encourage shallow root development.

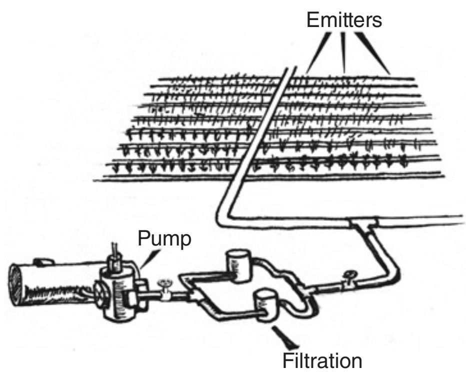

Fig. 10.7. Pressurized drip irrigation system.[50]

Other forms of irrigation

Of course, there are several other ways to spread water across the field. This chapter leaves out more specialized formats of pressure irrigation as well as many types of hand-watering and standard level-field flood irrigation. For more detailed information about planning, sizing and installing different types of irrigation system, consult the references listed in the further reading box below.

Further reading – Irrigation methods

Irrigation Water Management: Irrigation Methods, by Brouwer, C. *et al*. and produced by the Food and Agriculture Organization of the United Nations (FAO). *fao.org*. Available at: http://www.fao.org/docrep/s8684e/s8684e00.htm

Irrigation Water Management by Majumdar, D.K., 2010, (published by PHI Learning Private Limited, New Delhi).

Water application methods, a chapter (pp. 35–63) in *Practices of Irrigation & On-farm Water Management*, Volume 2 by Ali, M.H., 2011 (published by Springer, New York).

Irrigation Efficiency

The overall efficiency of an irrigation network, known as *irrigation water use efficiency* or simply as *irrigation efficiency* E_i, represents the percentage of water extracted for use in irrigation that will ultimately be delivered to the root zone of plants. As introduced in Chapter 1, overall irrigation efficiency will depend on the distinct efficiencies of its various components. It is thus difficult to assign an overall efficiency value to each of the irrigation methods described above. In general, moving water over the surface of the land is very inefficient because of high seepage and evaporation losses, so surface irrigation methods tend to be much less efficient than micro-irrigation, sprinklers or drip irrigation. Sprinkler irrigation can also have poor efficiency if pipes and sprinkler heads are not carefully designed and calibrated to deliver water evenly and at the right height.

Efficiency ratings for irrigation systems are typically divided into separate values for the storage system, conveyance network, and application method. The focus here is on the latter two terms.

Conveyance efficiency (E_c) is the efficiency of the water conveyance network that carries water from a storage structure or water source to the field. In surface irrigation systems, the conveyance network is a system of channels and furrows, while in pressurized irrigation it is a network of pipes and accessories. Well-sealed pipe networks, or lined concrete channels, will provide the highest conveyance efficiencies. Conveyance efficiency is determined by measuring water flowrates and calculating the ratio between the total water volume available at the outlet point of the conveyance network (Water OUT) and the water volume sent into the network (Water IN).[51]

Equation 10.1

$$E_c\,(\%) = \frac{Water\ OUT}{Water\ IN} \times 100\%$$

Application efficiency (E_a) is used to gauge the ability of the application system (e.g. sprinklers or level basins) to direct irrigation water toward the base of the plant and into the soil. It is expressed as the percentage of water originally delivered to the field (from the outlet of the conveyance network) that is effectively diverted to the root zone of crop plants.[52] Application efficiency is therefore impacted by water loss to evaporation and runoff, and by system design. Overall application efficiency is closely linked to application *uniformity*, a measure of the evenness of water distribution over the entire field.

Equation 10.2

$$E_a\,(\%) = \frac{Water\ delivered\ to\ the\ root\ zone}{Water\ delivered\ to\ the\ field} \times 100\%$$

The overall irrigation efficiency is the product of these combined:

Equation 10.3

$$Irrigation\ efficiency = Conveyance\ efficiency \times Application\ efficiency$$
$$E_i\,(\%) = E_c \times\ E_a \times 100\%$$

Where conveyance and application efficiency ratios are expressed as decimals (E = water OUT/water IN, without multiplying by 100%).

The FAO (1992) suggests that the typical efficiencies of surface, sprinkler and drip irrigation are 60%, 75% and 90%, respectively.[53] Of course, this varies by case. Irrigation efficiency is generally low in areas where storage structures and conveyance networks tend to be poorly sealed. Note that investments in irrigation efficiency may save costs associated with moving water, but do not necessarily directly equate to improvements in water productivity. Water leaked from irrigation networks is not 'lost' in the traditional sense, since most is ultimately returned to the groundwater or surface water system and remains available for subsequent use.[54] From a watershed perspective, the most direct benefit in terms of water productivity will come from reducing evaporation from the soil surface, storage reservoirs, and conveyance structures.

References

1 Food and Agriculture Organization of the United Nations (FAO), 1997. *Small-scale Irrigation for Arid Zones: Principles and Options*. Rome: FAO, p. 7.

2 Wani, S.P. *et al*., 2009. *Rainfed Agriculture: Unlocking the Potential*. Wallingford, UK: CABI, p. 204.

[3] Oweis, T., 1997. *Supplemental Irrigation*. Aleppo, Syria: International Center for Agricultural Research in the Dry Areas (ICARDA), p. 15.

[4] Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 193.

[5] Ibid.

[6] Adapted from Majumdar, D.K., 2010. pp. 193–195.

[7] Adapted from Ali, M.H., 2011. Water application methods, in *Practices of Irrigation & On-farm Water Management,* Volume 2. New York: Springer, p. 41.

[8] Adapted from FAO, 1997. *Small-scale Irrigation for Arid Zones*. Rome: FAO, p. 7.

[9] Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 197.

[10] Ali, M.H., 2011. Water application methods, in *Practices of Irrigation & On-farm Water Management*, Volume 2. New York: Springer, p. 45.

[11] Ibid.

[12] Anschütz, J. *et al*., 2003. *Water Harvesting and Soil Moisture Retention*, M. Nederlof & J. Anschütz, eds. Wageningen, The Netherlands: Agromisa Foundation, p. 68.

[13] Adapted from (i) Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, pp. 196–199; and (ii) Ali, M.H., 2011. Water application methods, in *Practices of Irrigation & On-farm Water Management*, Volume 2. New York: Springer, pp. 43–45.

[14] Adapted from Ali, M.H., 2011. Water application methods, in *Practices of Irrigation & On-farm Water Management*, Volume 2. New York: Springer, p. 44.

[15] Adapted from FAO, 1997. *Small-scale Irrigation for Arid Zones: Principles and Options*. Rome: FAO.

[16] Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 189.

[17] Ibid.

[18] Ibid.

[19] Adapted from Ibid. pp. 188–192.

[20] Adapted from Ali, M.H., 2011. Water application methods, in *Practices of Irrigation & On-farm Water Management*, Volume 2. New York: Springer, p. 40.

[21] Brouwer, C. *et al*., 1988. *Irrigation Water Management: Irrigation Methods*. Rome: FAO. *fao.org*. Available at: http://www.fao.org/docrep/s8684e/s8684e00.htm [Accessed June 18, 2014].

[22] Varma, S. *et al*., 2006. *Promoting Micro-irrigation Technologies that Reduce Poverty*. Colombo: International Water Management Institute (IWMI), pp. 2–3.

[23] Ali, M.H., 2011. Water application methods, in *Practices of Irrigation & On-farm Water Management*, Volume 2. New York: Springer, p. 53.

[24] Awulachew, S.B. *et al*., 2009. *Irrigation Methods: Drip Irrigation— Options for Smallholders*. International Livestock Research Institute (ILRI): Addis Ababa, p. 211. *ilri.org*. Available at: https://cgspace.cgiar.org/bitstream/handle/10568/80/Modules1_5.pdf?sequence=6 [Accessed June 10, 2016].

[25] Ibid.

[26] Ibid.

[27] Adapted from Ibid.

[28] Adapted from FAO, 1997. *Small-scale Irrigation for Arid Zones: Principles and Options*. Rome: FAO.

[29] Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 216.

[30] Bhople, B.S. *et al*., 2014. Sub-surface method of irrigation – clay pipe irrigation system. *IOSR Journal of Agriculture and Veterinary Science*, 7(11), p. 61.

[31] FAO, 1997. *Small-scale Irrigation for Arid Zones: Principles and Options*. Rome: FAO, p. 15.

[32] United Nations Environment Programme (UNEP), 1999. *Sourcebook of Alternative Technologies for Freshwater Augmentation in Africa*. *unep.or.jp*, p. 182. Available at: http://www.unep.or.jp/ietc/publications/techpublications/techpub-8a/ [Accessed September 26, 2012].

[33] Ibid.

[34] FAO, 1997. *Small-scale Irrigation for Arid Zones: Principles and Options*. Rome: FAO, p. 17.

[35] Adapted from: (i) FAO, 1997; and (ii) UNEP, 1999. *Sourcebook of Alternative Technologies for Freshwater Augumentation in Africa*. *unep.or.jp*, p. 182. Available at: http://www.unep.or.jp/ietc/publications/techpublications/techpub-8a/ [Accessed September 26, 2012].

[36] Adapted from FAO, 1997. *Small-scale Irrigation for Arid Zones: Principles and Options*. Rome: FAO.

[37] Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 208.

[38] Ibid. p. 207.

[39] Ali, M.H., 2011. Water application methods, in *Practices of Irrigation & On-farm Water Management*, Volume 2. New York: Springer, p. 46.

[40] Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 211.

[41] Ibid.

[42] Adapted from Majumdar, D.K., 2010. p. 208.

[43] Adapted from FAO, 1997. *Small-scale Irrigation for Arid Zones: Principles and Options*. Rome: FAO, p. 8.

[44] Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 214.

[45] FAO, 1997. *Small-scale Irrigation for Arid Zones: Principles and Options*. Rome: FAO, p. 21.

[46] Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 214.

[47] Ibid.

[48] Ibid. p. 215 with data from Sivanappan, R.K., 1975. Economics of drip irrigation method in small and marginal farms. Paper presented at the XVth Annual Convention of the Indian Society of Agricultural Engineers, Pune, India.

[49] Adapted from: (i) Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, pp. 214–215; and (ii) Ali, M.H., Water application methods, in *Practices of Irrigation & On-farm Water Management*, Volume 2. New York: Springer, p. 54.

[50] Adapted from FAO, 1997. *Small-scale Irrigation for Arid Zones: Principles and Options*. Rome: FAO, p. 20.

[51] Kijne, J.W. *et al*., 2003. *Water Productivity in Agriculture*. Wallingford, UK: CABI, p. xiii.

[52] Ibid.

[53] Kay, M. & Hatcho, N., 1992. *Small-scale Pumped Irrigation: Energy and Cost*. Rome: FAO, p. 37.

[54] Molden, D. *et al*., 2003. A water-productivity framework for understanding and action, in J. Kijne *et al*., eds, *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. Wallingford, UK: CABI, p. 4.

11 Irrigation Scheduling

Goals of Irrigation Scheduling

As introduced in Chapter 3, only a portion of the water held in the soil is available to plant roots. The soil itself will have a certain water holding capacity (field capacity), above which point no new water can be stored. Within that capacity, part of the water (below wilting point) is never accessible to plants. Stored soil water between field capacity and the wilting point is called *available* water. Of this quantity, only part (typically 20–80%) will be *readily available* to the crop plant, and this proportion will vary by species.[1] The goal of irrigation scheduling is to ensure that the soil always maintains some degree of readily available water within the crop's root zone. Below the *critical point* of minimum readily available water, the plant suffers irreversible water stress and its yield is reduced.[2] Soil water content conditions that lie below field capacity but above this critical point are considered to fall within the *optimal range* of soil moisture for plant development (Fig. 11.1).

In some forms of conventional full irrigation, the goal of water application is to bring the soil back to full field capacity so that the crop's access to available water in the root zone is not constrained in any way. Water is applied at regular intervals, often with little regard to the quantity of water used. While this approach provides good production, it does not encourage a sustainable use of water. Although some argue that water stress conditions begin immediately below full field capacity, crop plants are generally capable of producing good yields within the range of optimal soil water conditions.[3] Excess water application is not only a wasteful use of the resource, it contributes to nutrient leaching and water pollution. In water-constrained environments, maintaining near-field capacity levels of soil moisture through frequent water application is not justified.[4]

In supplemental irrigation, the goal of water applications is rarely the full restoration of field capacity moisture levels. Supplemental irrigation involves only

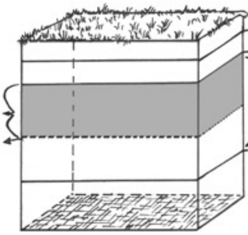

Fig. 11.1. Optimal range of soil moisture.

occasional application of 'supplementary' water to primarily rainfed crops, with the goal of ensuring that plants have access to sufficient water during critical growth stages that have a significant effect on yields. Because water availability for irrigation is limited, the amount of water added should be the minimum quantity needed to produce an acceptable yield.[5] The goal of water applications in this case is to restore soil moisture to an adequate level of available water, within the optimal range.

Irrigation Water Requirement

The depth of water applied to restore soil moisture with each irrigation is commonly known as the *irrigation depth* (ID). It is conventionally defined as the difference between soil moisture at the time of irrigation and field capacity, or some portion thereof. The *irrigation water requirement* (IRR) of the crop, on the other hand, is the actual water needed, beyond rainfall, to provide for the full crop water requirement (ET_c, Chapter 4). The latter value is useful because it allows for the planning of water applications according to need, but it is also more difficult to calculate. It relies on accurate estimates of ET_c, to which existing soil moisture (due to rainfall or previous irrigation events) and water losses must be factored in. Though this method can be difficult to use on an ongoing basis, it is useful to understand actual crop water needs in order to promote an efficient use of water.

Calculating irrigation depth

The simplified version of irrigation depth, represented here as ID, is determined using soil moisture information, which is either measured directly or estimated in advance based on a set schedule. The most basic calculation of ID is the difference between the current soil water content (SWC) and total field capacity (FC) over the effective root depth of the crop.

Equation 11.1[6]

$$ID = (FC - SWC) \times d/100$$

Where ID is the irrigation depth (net water requirement per irrigation event, in centimeters), FC is the field capacity (soil water holding capacity, in percentage volume), SWC is the soil water content before water application (also in percentage volume), and d is the depth of the plant's root zone, in centimeters.

This calculation gives us an idea of how much soil water would ideally be replenished during water application if the goal is to restore full field capacity. If some percentage of FC (within the optimal range) is desired instead, this proportion is used in the ID calculation in place of the full FC value.

This calculation does not take into account the efficiency of water application. The total volume to be applied when compensating for conveyance and application efficiencies is known as the *gross irrigation depth* (GID).[7]

Equation 11.2[8]

$$GID = ID/(E_c \times E_a)$$

Where GID is the gross irrigation depth (in centimeters), ID is as defined above, E_c is the irrigation conveyance efficiency and E_a is the irrigation application efficiency.

The irrigation depth value, when multiplied by the field area, yields a volume of water delivered with each application. This simple calculation provides a useful guideline for measuring individual irrigation events. However, it doesn't provide complete information about the amount of water actually required to provide for the crop. In this respect, it is useful to estimate the actual irrigation required (IRR) to meet the crop's full water demand using the water budget approach (Chapter 2):

Equation 11.3: The water budget

$$IRR + P + Cap = ET_c + Roff + Tx + D + E$$

The left side of the equation sums up the water inputs to the soil (irrigation, precipitation, and capillary rise from shallow groundwater) and must balance with the right side, which includes all water outputs (crop water use, runoff, weed transpiration, deep percolation, and evaporation). The equation can be rearranged to yield:

Equation 11.4[9]

$$IRR = ET_c + Roff + Tx + D + E - P$$

(Unless a shallow groundwater table is present, Cap can be removed.) ET_c is calculated based on the methods outlined in Chapter 4, and precipitation (P) can be determined by researching yearly or monthly precipitation averages for the region. The remaining outputs, however, are difficult to determine with accuracy. This method is therefore highly imprecise unless some estimate of rainfall partitioning in the crop system is available. Brouwer and Heibloem (1986) suggest a simplified method for using the water budget approach to determine monthly irrigation water requirements.[10] It is based on two shortcut formulas:

Equation 11.5a

$$Pe = 0.8\,P - 25 \text{ if } P > 75 \text{ mm/month}$$
$$Pe = 0.6\,P - 10 \text{ if } P < 75 \text{ mm/month}$$

Where Pe is *effective* precipitation received each month, a value that deducts water loss values from the precipitation amount (i.e. $Pe = P - Roff - Tx - D - E$). Combining this with equation 11.4 yields:

Equation 11.5b

$IRR = ET_c - (0.8\ P - 25)$ if rainfall is over 75 mm that month, or
$IRR = ET_c - (0.6\ P - 10)$ if rainfall is less than 75 mm.

Where IRR and ET_c are expressed in mm/month.

This method requires finding ET_c values per month, and matching them with the timing of the crop's growth stages throughout the year. The resultant total irrigation requirement per month or for the full growing season can be divvied up and used as a basis for water applications. The results are not accurate for every case because of the large number of assumptions made, but this is a useful exercise for those looking to better understand the water needs of their chosen crop throughout the season. For detailed instructions on using this method, consult the full reference from Brouwer and Heibloem in the further reading box at the end of this section.

Sometimes, auxiliary water demands for functions other than irrigation must be added to ID and IRR values. These depend on soil, plant, and climate characteristics. Some examples of auxiliary water demands include:[11]

- Water required for land soaking (prior to initial field preparation).
- Water required for land preparation (prior to planting).
- Water required for soil leaching (in the case of saline soils, an added volume of water is applied with irrigation in order to assist in the leaching of salts from the soil).

To include the volumes needed for these functions, extra water is added to the depth of a particular irrigation event (in the case of soaking and preparation) or to all irrigation events throughout the season (in the case of the leaching demand).

In saline soil or water conditions, water applications may need to be calculated differently. Salt affects the ability of plants to extract water from the soil, so added amounts can be required to provide the same amount of moisture to the soil. See Chapter 12 for more information about salinity.

Water applied in supplemental irrigation

When supplemental irrigation is practiced, rather than seeking to supply the full IRR amount, water application is planned to ensure a minimum amount of available soil water is maintained during critical growth stages. In water-constrained environments where supplemental irrigation is practiced, it is neither practical nor beneficial to seek to restore the soil to full field capacity with each water application. In these cases, alternate methods are used to determine irrigation water required – some examples include:[12]

- Applying a chosen depth of water with each application, determined according to the relationship between rainfall and seasonal crop water requirement. This depth can be uniform throughout the season, or modified for each growth stage (e.g. 50 mm at sowing, 100 mm at flowering, etc.). The ideal depth and timing of supplemental irrigation events can be refined through experience and observation, informed by rainfall conditions each season and the feel of the soil and the plants.

For example, research in the West Asia/North Africa region has indicated that between one and three water applications per growing season, each of no more than 100 mm, has been successful in improving wheat yields.[13]

- Using a trial-and-error approach to determine how much water is needed to produce a profitable crop yield within available water supplies. This is done by weighing the benefit of yield improvements from irrigation against the cost or availability of water for irrigation. The amount of water applied is manipulated over successive seasons to find the point at which the yield benefit:water applied ratio ($WUE_{(IRR)}$, Chapter 1), is most favorable. After this point, further improvements in the product may not be worth the added water invested.

For example, trials with supplemental irrigation of wheat fields in Syria found that supplying 50% of the total seasonal irrigation requirement (IRR) amount was most profitable. Yields achieved when supplying full IRR were only 10–15% higher than at 50% IRR, so the water added after that point provided only a small benefit in terms of water use efficiency. Instead, the water saved allowed for more land to be brought into production, which significantly increased the yield benefit of the water.[14]

Applications of supplemental irrigation are not often planned in advance, but rather are added in response to dry spells occurring during the growing season. The farmer can choose at the time of irrigation how much water to apply. Because over-irrigation is not good for the crop or the water supply, measuring the applications based on need and water use efficiency is advantageous. The $WUE_{(IRR)}$ function (Chapter 1) can be used to compare the comparative yield benefit derived from different amounts of added water.

Further reading – Irrigation water requirement

Irrigation Water Management: Irrigation Water Needs, a training manual by Brouwer, C. & Heibloem, M., 1986, for the Food and Agriculture Organization of the United Nations (FAO). Available at: ftp://193.43.36.92/agl/AGLW/fwm/Manual3.pdf

Supplemental Irrigation: A Highly Efficient Water-use Practice, 2nd edn, written by Oweis, T. & Hachum, A., 2012, for the International Center for Agricultural Research in the Dry Areas (ICARDA). Available at: http://www.icarda.org/wli/pdfs/Books/Supplemental_Irrigation.pdf

When to Irrigate

The scheduling of water applications is possibly even more important than irrigation amount. Careful timing of irrigation events is vital in the effort to improve water productivity because it affects the degree to which the water added will be useful. *Irrigation scheduling* depends on a range of considerations including soil moisture conditions, soil type and management, crop type, growth stage, climate and rainfall predictions, and irrigation method.[15]

Proper timing of irrigation events provides benefits for:

- Plant health and expected yields – by optimizing the amount of water and oxygen that are available to plant roots at different points over the growing season.
- Water use and water withdrawals – by watering only when necessary and limiting water lost to evaporation, runoff and deep percolation.
- Energy use and labor requirement – by operating irrigation equipment only when necessary.
- Fertilizer requirement – by improving the impact of fertilizer applications.
- Soil health – by controlling soil moisture conditions during and after irrigation events, and preventing saturation conditions which contribute to leaching.
- The environment – by limiting the amount of agricultural pollution, controlling salinity, and creating a healthy moisture environment that does not contribute to the proliferation of pests and disease.

Some farms that practice full irrigation take a simplified approach to irrigation scheduling, and plan water applications at regular intervals throughout the growing season. The requirement of a set schedule is also often built into water allocation schemes. This type of scheduling disregards rainfall inputs and climate variations from season to season. The result can be poor irrigation efficiency and lost potential for improved yields. This practice can also be harmful to the environment if excess water is applied.[16] Irrigation scheduling based on more precise intra-seasonal conditions helps to keep the field environment clean and safe, and is the key to creating an optimal soil moisture environment for plant growth.

Irrigation scheduling approaches

Irrigation is typically scheduled to apply water when a pre-determined low point of readily available soil water is reached. This point, expressed as a percentage of available soil water, is often called the *critical level of soil moisture*, or sometimes expressed as the *maximum allowable soil water depletion*, its inverse value.[17] For example, if a bean crop begins to experience stress when available water drops to 60% of available water, then the critical level of soil moisture for the bean plot is 60%, and its maximum allowable soil water depletion is 40%. Both values are expressed as percentages of available water at field capacity (FC-WP, Chapter 3).

Soil moisture sensors and crop monitoring equipment will provide the most reliable information for irrigation scheduling, but this technology is not available to most smallholder farmers. Some simpler, low-cost irrigation scheduling approaches include: (i) the crop observation method; (ii) the soil water balance/calendar method; and (iii) the critical stages method.

Crop observation method

The simplest method of irrigation scheduling involves careful observation of the crop stand, through which the farmer will learn (if he/she does not know already) to recognize the signs of water stress in the plant foliage. Common symptoms of water stress include yellowing or curling leaves, and reduced turgor pressure causing wilting or drooping. Note that on hot, sunny days, even healthy plants with sufficient access to water can show signs of drooping. However, if these symptoms are visible in the early mornings, water application is required. Some plants will also display color changes when they are stressed, often starting from the lower leaves.[18]

Every plant reacts differently to water stress conditions. This method is most effective with crops that display water stress effects very soon after water deficit conditions begin. The disadvantage of this method is that by the time that plant water stress becomes visible, damage has already occurred. Alternatively, plants of an ‘indicator crop’, which readily and visibly reacts to water stress, can be added to the crop stand in order to signal soil moisture deficit.[19] The indicator species should be planted at various locations within the crop rows.

Soil water balance/calendar method

The soil water balance or calendar method uses calculated values of daily crop water requirement (ET_c, Chapter 4) to determine the number of days between irrigation events. Available soil moisture is treated like a bank account, and withdrawals and deposits of water are diligently recorded. Plants are assumed to deplete soil water at their daily ET_c rate, or at a given proportion of daily ET_c chosen to approximate actual evapotranspiration, ET_a. Soil water content is measured at the season start, and ET_c values are used to determine the number of days that it will take to reach the critical level of soil water. Irrigation events are scheduled accordingly.

Because this method is imprecise, soil moisture should be checked periodically throughout the season to validate estimates made. Atmospheric conditions, irrigation events and rainfall should be recorded daily. Ultimately, this detailed record can help to identify patterns in the calendar and associate them with water stress and yield impacts.

This method is rather simplistic and tends to overlook factors (such as runoff, weed growth, percolation, and irrigation efficiency) that influence the translation of irrigation water into available soil moisture.[20]

Critical stages method

When available soil water is depleted past the critical point, the plant becomes stressed. This stress has a negative impact on yields – however, the degree of this impact varies according to the growth stage at which the water stress is experienced. During some growth stages, water stress will have only a small impact on potential yields, while during others, this same degree of stress would be highly detrimental. In the critical stages approach to irrigation scheduling, water applications are timed to coordinate with the crop growth stages during which soil moisture is most influential to crop yield. Irrigation is scheduled in order to ensure that the soil contains an optimum level of available water at the onset of these critical growth stages, which vary by crop. Optimal soil moisture is maintained as much as possible during that stage, and then allowed to fall off. In some cases, artificial drainage may instead be required if wet conditions coincide with growth stages that are especially sensitive to waterlogged soils.

The critical stages approach is especially relevant in areas with limited water supplies. The timing of water applications around critical stages forms the basis of both supplemental and deficit irrigation (explained below). Supplying water just prior to and during critical growth stages will provide the most crop benefit per unit of water applied as irrigation, thereby maximizing water use efficiency.[21]

The critical growth stages of various crops are widely documented in agricultural literature. Table 11.1 provides examples for some common crops according to D.K. Majumdar, 2010.[22]

Table 11.1. Critical growth stages for common crops.[23]

Crop	Critical growth stages (in order of decreasing importance)
Rice	Flowering, grain filling, tillering, panicle initiation, transplanting
Maize (corn)	Tasseling and silking, grain filling, knee height
Wheat	Crown root initiation, flowering, jointing, milk and dough stages
Sorghum	Flowering, seedling, grain filling
Groundnut (peanut)	Pegging, pod setting, pod filling
Soybean	Flowering, pod development, branching
Sunflower	Flowering, seed filling four- to six-leaf

Under supplemental irrigation, water can be required only a few times per growing season, when climate conditions limit the available soil water either before or during a critical growth stage. Water applications are timed according to the onset of critical stages, so practitioners of supplemental irrigation should become familiar with the critical growth stages of their chosen crop(s).

The soil water available at planting also has a strong influence on yields. Scheduling one water application at the time of sowing has proven to be beneficial for several crop varieties in experiments with supplemental irrigation.[24] Water application early in the season also allows for early planting, which can improve both yields and water use efficiency.[25] If only one irrigation is planned per season, some research suggests it may have the most beneficial impact at the time of planting.[26] The relative benefit of sparse water applications on various crops under supplemental irrigation is a subject of ongoing research. Specific information about the ideal timing and amount of water applications in supplemental irrigation can sometimes be found in regional resources and research reports.

Deficit Irrigation

In most arid and semi-arid regions, water is a more significant limiting factor for crop production than land. In these cases, farm income from irrigated plots consists of profits from crop products less the costs of water and irrigation equipment. Water also carries an *opportunity cost*: if water is saved on one plot, there is potential to use these savings to bring more land into production.[27]

Deficit irrigation, also sometimes called partial irrigation, is the practice of purposefully under-irrigating a crop that would otherwise be fully irrigated. It involves the selective elimination or reduction of irrigation within certain stages of plant development for which the yield impact of water stress is known to be minimal. Valuable water supplies are 'saved' through reduced water applications in favor of providing optimal soil moisture during critical growth stages when yield impact is greatest. Deficit irrigation is a very promising method for maximizing water productivity on irrigated farms located in water-scarce regions.

In certain cases, water stress may even enhance the quality of the crop by directing water to support the grain/fruit portion instead of the straw portion, and/or by improving the grain size, protein content, and sugar content of the crop product.[28] By manipulating these plant mechanisms with selective irrigation, the profit derived from available water can be maximized.

Methods of deficit irrigation include the following (or any combination of these):[29]

1. Reducing irrigation depth (amount).
2. Eliminating some irrigation events during non-critical growth stages.
3. Extending the interval between irrigation events.
4. Allowing soil moisture to drop to a level lower than in full irrigation.
5. Wetting alternate furrows (in the case of furrow irrigation).

Deficit irrigation can have a number of advantages, including:[30]

- increased irrigation efficiency;
- increased water productivity;
- reduced water losses due to deep percolation, runoff, and evaporation;
- reduced nutrient leaching from the root zone;
- mitigation of the harmful effects of irrigation (as outlined in the Preamble to Part 3);
- enhanced yield quality in some cases; and
- improved root development and overall drought resistance.

The main disadvantage of deficit irrigation is a heightened risk of inducing plant water stress by reducing water application. Full knowledge of the crop's reaction to water stress in different growth stages is the best weapon for reducing risk and establishing an effective deficit irrigation regime. Note that in saline conditions, deficit irrigation should be carefully administered, since the salt leaching effects of water application will be minimal. Auxiliary water applications for soil flushing will be necessary in these conditions.[31]

Before implementing deficit irrigation, farmers should familiarize themselves with the drought sensitivity of their chosen crop(s) throughout successive stages of development. Because the effects of drought are also influenced by climate, cropping pattern, and other site-specific factors, detailed analysis is necessary to determine a deficit irrigation regime for a given farm. See the further reading box at the end of this section for additional references that can be useful for designing a deficit irrigation scheme.

Further reading – Deficit irrigation

Deficit Irrigation Practices, a collection of research assembled by the FAO. Available at: http://www.fao.org/docrep/004/y3655e/y3655e00.htm

Crop yield response to water, produced by the FAO. Available at: http://www.fao.org/docrep/016/i2800e/i2800e.pdf

Drainage

The presence of excess water in the root zone has a significant negative effect on plant development: not only does it limit the availability of needed oxygen to the plant's root system, it also restricts plant uptake of nutrients and impedes the decomposition of organic matter, which is so crucial to soil health. Over time, poorly drained soils can lead to rising water tables and associated salinity problems.[32] Drainage is very important in irrigated agriculture. Too often, drainage problems on irrigated farms are not addressed until it is too late, and the land has already been degraded by waterlogging and salinization.[33]

Land prone to surface pooling and waterlogging can be rehabilitated through the installation of *artificial drainage networks* designed to draw water away from the subsoil area. Drainage is especially important for fields under full irrigation, but it can also be generally beneficial for clay-rich or otherwise poorly drained soils in areas prone to heavy rainfall or flooding. Land near unlined water conveyance or storage structures may also benefit from added drainage. In general, soils that are poorly drained will appear soggy and soft, and will readily stick to farm tools. Crops grown in poor drainage conditions will appear yellowed and stunted.[34] When permanently saturated soil layers (shallow water tables) are encountered at less than 200–300 cm from the surface (depending on soil type), the soil is considered to be poorly drained and at risk of salinization if irrigation is practiced.[35, 36]

While most drainage infrastructure is designed to function by gravity, some systems may also incorporate pumping. Common methods of drainage can be divided into two categories: (i) surface drainage; and (ii) subsurface drainage.

Surface drainage

Surface drainage is used to drain away excess water received during rain or irrigation events. Land is graded to promote the drainage of excess water by gravity toward a network of drainage channels distributed across the field surface. Drainage channels are installed in a regular pattern (on flat fields) or an irregular pattern (on undulating terrain) designed to intercept the natural flow of water along the surface. In-field channels are sloped to drain toward larger collector drains which themselves eventually outflow toward a water body or a part of the field where water can safely accumulate (Fig. 11.2). On sloping lands, channels created laterally across the slope can divert surface runoff and reduce water accumulation in low-lying areas. Drainage water can be captured in a storage structure and later reused in irrigation if its quality is sufficient.[37]

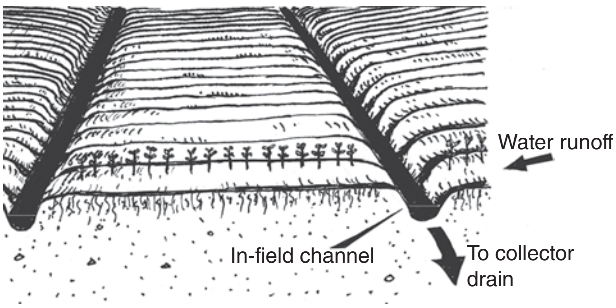

Fig. 11.2. Surface drainage.[38]

Subsurface drainage

Subsurface drainage is used to prevent the accumulation of excess soil water within the rooting zone of crops. *Tile drainage* or *pipe drainage* involves laying buried perforated piping below the root zone in an even distribution pattern (Fig. 11.3). Typical pipe depths range from 0.8 m to 1.5 m.[39] When salinity is a concern, deeper drains of 2 m or more can be required.[40] Concrete or clay tiles (pipe sections) are commonly used for this application, but plastic piping is becoming increasingly widespread in some areas. Bamboo, wood poles, or stone slabs can also be used as an alternative material for low-cost pipe drainage construction.[41] Pipes should be surrounded by loose stones or another fast-draining material in order to prevent clogging of perforation holes. Drain lines are laid at a gentle slope toward the edge of the field where they can empty into a collection drain or an open channel which will eventually empty into a water body or a part of the field where water can safely accumulate. If drainage runoff is reused, water empties into a storage reservoir. Tile drainage is expensive and labor-intensive to install, but it can create an excellent environment for plant growth in areas with shallow water tables.[42] *Deep open drains* are a less costly method of providing subsurface drainage (Fig. 11.3). These are deep, narrow drainage channels that are dug (usually by machine) to a depth below the level of shallow water tables. Water drains from the saturated subsoil toward these open drains, effectively lowering the water table to a level that allows crop growth. Unlike tile drainage, this method results in a loss of cultivable area. Deep open drains are only suitable for small fields with stable and compactable soils.[43]

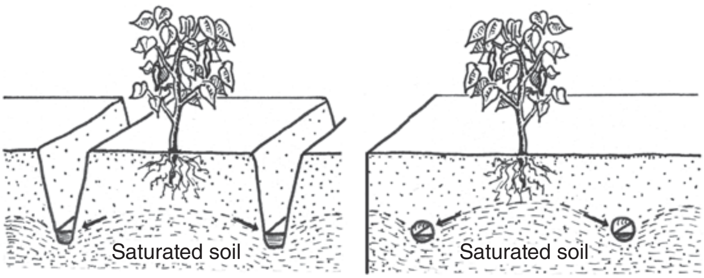

Fig. 11.3. Subsurface drainage methods: deep open drains (left) and tile or pipe drainage (right).[44]

Further reading – Drainage

Agricultural drainage water management in arid and semi-arid areas. *FAO Irrigation and Drainage Paper* #61. Available at: http://www.fao.org/docrep/005/y4263e/y4263e00.HTM

References

[1] Allen, R.G. *et al*., 1998. *Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements*. Rome: Food and Agriculture Organization of the United Nations (FAO). *fao.org*. Available at: http://www.fao.org/docrep/X0490E/x0490e00.htm [Accessed December 6, 2012].

[2] Terminology from Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 262.

[3] Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 63.

[4] Ibid. p. 264.

[5] Oweis, T. & Hachum, A., 2012. *Supplemental Irrigation: A Highly Efficient Water-use Practice*, 2nd edn. Aleppo, Syria: International Center for Agricultural Research in the Dry Areas (ICARDA), p. 8.

[6] Ali, M.H., 2010. Crop water requirement and scheduling, in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, p. 407.

[7] Ibid.

[8] Ibid.

[9] Adapted from Ali, M.H., 2010. Crop water requirement and scheduling, in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, p. 405.

[10] Copied with permission from Brouwer, C. & Heibloem, M., 1986. *Irrigation Water Management: Irrigation Water Needs*. Training Manual. Rome: FAO. Available at: ftp://193.43.36.92/agl/AGLW/fwm/Manual3.pdf [Accessed February 15, 2015].

[11] Ali, M.H., 2010. Crop water requirement and scheduling, in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, p. 403.

[12] Oweis, T., 1997. *Supplemental Irrigation*. Aleppo, Syria: ICARDA, p. 11.

[13] Oweis, T. & Hachum, A., 2012. *Supplemental Irrigation: A Highly Efficient Water-use Practice*, 2nd edn. Aleppo, Syria: ICARDA, p. 10.

[14] Ibid.

[15] Ali, M.H., 2010. Crop water requirement and scheduling, in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, p. 410.

[16] Ibid.

[17] Critical level terminology from Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 262.

[18] Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 268.

[19] Ibid.

[20] Ali, M.H., 2010. Crop water requirement and scheduling, in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, pp. 399–452.

[21] Ibid. p. 422.

[22] Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 266.

[23] Ibid.

[24] Caliandro, A. & Boari, F., 1996. Supplementary irrigation in arid and semiarid regions. *A Mediterranean Journal of Economics, Agriculture and Environment (MEDIT)*, 1(96), pp. 24–27.

[25] Oweis, T., 1997. *Supplemental Irrigation*. Aleppo, Syria: ICARDA.

[26] Humphreys, E. *et al*., 2008. *Improving Rainwater Productivity: Topic 1 synthesis paper*. Colombo: CGIAR Challenge Program on Water and Food, 19 pp.

[27] Ali, M.H., 2010. Crop water requirement and scheduling, in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, p. 418.

[28] Ibid. p. 421.

[29] Ibid.

[30] Ibid.

[31] Ibid.

[32] Brouwer, C. *et al*., 1985. *Irrigation Water Management: Introduction to Irrigation*. Rome: FAO.

[33] FAO, 1997. *Small-scale Irrigation for Arid Zones: Principles and Options*. Rome: FAO.

[34] Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 421.

[35] Ibid.

[36] Stockle, C.O., 2001. *Environmental Impact of Irrigation: a Review*. Pullman, Washington: State of Washington Water Research Center, p. 7.

[37] Tanji, K.K. & Kielen, N.C., 2002. Agricultural drainage water management in arid and semi-arid areas. *FAO Irrigation and Drainage Papers*, (61), p. 205.

[38] Adapted with permission from Brouwer, C. *et al*., 1985. *Irrigation Water Management: Introduction to Irrigation*. Rome: FAO.

[39] Ali, M.H., 2011. Drainage of agricultural lands, in *Practices of Irrigation & On-farm Water Management*, Volume 2. New York: Springer, p. 331.

[40] Ayers, R.S. & Westcot, D.W., 1985. *Water Quality for Agriculture*. Rome: FAO. Available at: http://www.fao.org/docrep/003/T0234E/T0234E00.htm [Accessed March 6, 2013].

[41] Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 429.

[42] Ibid. p. 426.

[43] Ali, M.H., 2011. Drainage of agricultural lands, in *Practices of Irrigation & On-farm Water Management*, Volume 2. New York: Springer, pp. 327–378.

[44] Adapted with permission from Brouwer, C. *et al*., 1985. *Irrigation Water Management: Introduction to Irrigation*. Rome: FAO.

12 Water Sources for Agriculture

Especially in dryland environments, the fundamental prerequisite for irrigation development is a good and reliable source of water. When assessing a water source for use in agriculture, it is relevant to consider both the quantity and quality that will be accessible over time. If one of these factors proves to be insufficient, the harm caused by an irrigation project could outweigh its benefit in the long term.

This chapter addresses the character and quality of water sources commonly used to supply irrigation projects. It also introduces some water contaminants of special concern, and provides a brief overview of water-lifting devices traditionally employed on small farms.

Water Quantity

The quantity of water readily available from a blue water source is difficult to assess with accuracy, since water levels, stream size and groundwater flows fluctuate significantly over time. Climate, rainfall, and the activities of upstream users all have a strong influence on the quantity of water that will be accessible from a blue water source at a given point in time.

It is also important to consider the needs of other users of the resource – both human and non-human. The over-extraction of blue water sources for use in agriculture is an unfortunate reality in many parts of the world, and especially in areas with a high degree of irrigation development.[1] Over-extraction of a blue water source not only affects other water users in the watershed, it can also cause significant ecological harm, which in turn threatens the availability of water in the future. Globally, countless rivers and lakes have been irreversibly altered by the extraction of water for use in irrigation. The drying of the Colorado River in California and the Aral Sea in central Asia are prominent examples of over-extraction.

Scientists use the term 'environmental flows' to designate the minimum blue water flow that is required to maintain the critical ecological functions of a watershed. The term encompasses not only the quantity of flow, but also rate, timing, and water quality. Water extractions can only be considered to be sustainable if environmental flows are maintained at all times.[2] As a relatively new science, values for environmental flows are not yet defined for all watersheds, though this kind of data is increasingly available from watershed management organizations and universities.

Beyond environmental uses, it is also vital to be respectful of downstream users when planning a water extraction project. Inequitable partitioning of water sources (e.g. by withdrawing water at a rate that compromises downstream users' livelihoods) can lead to conflict.

Measuring Irrigation Water

Irrigation water use, especially in low-efficiency practices such as surface irrigation, can be a significant source of both water and energy wastage, in part because water use is neither routinely measured nor monitored. In order to manage water responsibly, it is useful to quantify water flows on and off the farm. These measurements provide a basis for evaluating efficiency improvements.

1. Quantifying water flows onto the field

Irrigation water used in hand-watering or micro-irrigation can be measured volumetrically by monitoring the volume of water storage structures before and after an irrigation event, or by counting the number of re-fills made in each structure during water application. In surface and pressurized irrigation, the flow rate of rivers, open channels or pipes directing water onto the field can be used to estimate irrigation water volumes. The flow rate of streams, water diversion channels and irrigation ditches can be measured precisely using specialized equipment, or estimated using simplified area-velocity measurements (Fig. 12.1).

Equation 12.1: Area-velocity method for measuring channel flow[3]

$$Q = 0.85 \times A \times D/T$$

Where Q is the channel water flow rate in cubic meters per second (m^3/s), A is the cross-sectional area of the water flow at a given point (m^2), and T is the time the water flow takes to travel D meters in distance (in seconds) (see Fig. 12.1). Values for T can be estimated by timing the movement of a buoyant object or a partially submerged bottle down a chosen distance D (ex. 10 m) of the stream.[4]

The flow rate value (Q) can be expressed in liters, gallons, or other units, but for further steps it is simplest to express it in litres or cubic meters per second (1 m^3 = 1000 liters = 264 US gallons = 220 British gallons). Note that this method yields a very approximate measure of flow rate, but is simple to perform and doesn't require specialized equipment.

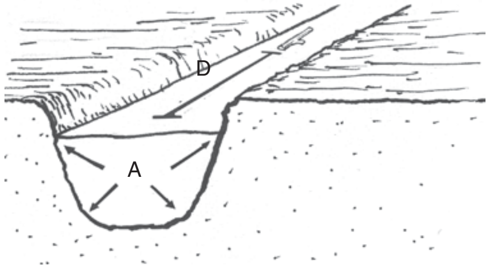

Fig. 12.1. Area-velocity measurements: A is the cross-sectional area of the water flow at a given point (m^2), and D is the distance in meters that the water flows in time T (in seconds).

Alternatively, if the channel, pipe or stream is small enough and can be made to discharge temporarily into a container, the flow rate can be determined by measuring the time it takes to fill a container of a known volume. The volume of the container is then divided by the number of seconds it took to fill. For example, if water flowing from a pipe fills a 20 l bucket in 40 seconds, the flow rate is 0.5 l/s.

Equation 12.2: Container method for measuring flow[5]

$$Q = V/t$$

Where Q is the flow rate (m^3/s), V is the volume of the container filled (in m^3), and t is the time that it takes to fill (in seconds).

The combined flow rates of all the channels, ditches or pipes used during irrigation water applications is the total irrigation flow rate, also known as the *application rate*.

Equation 12.3: Total irrigation flow rate/application rate

$$Q_{total} = Q_1 + Q_2 + Q_3, etc.$$

Where Q_1, Q_2, Q_3 and so on are the flow rates of each individual channel, pipe, or stream delivering water to the field.

2. Estimating the time required to reach full irrigation depth

Based on the total flow rate of irrigation water into the network, it is possible to estimate the time of water application required to provide the desired irrigation depth, as described in Chapter 11. Assuming the flow rate measurements in the first step were made upstream of most in-field conveyance and distributions elements of the irrigation network, this step requires that we incorporate conveyance and application efficiencies to compensate for water lost during application. Note that in this method, irrigation depths are expressed in meters, and times are expressed in seconds. This is done for simplicity, but frequent users of these formulas may want to add conversions to output irrigation depths in centimeters and time in minutes.

Equation 12.4: Time of irrigation required to meet desired irrigation depth, ID

$$T_{irrigation} = (GID \times A_{plot} / Q_{total})$$

or

$$T_{irrigation} = (ID \times A_{plot}) / (Q_{total} \times E_c \times E_a)$$

Where $T_{Irrigation}$ is the time of irrigation (in seconds), GID is the gross irrigation depth and ID is the net irrigation depth (in meters, see Chapter 11), A_{plot} is the area of the plot under irrigation (square meters, m^2), Q_{total} is the total flow rate of the application method (in cubic meters per second, m^3/s), E_c is the conveyance efficiency, and E_a is the application efficiency.

3. Total volume of water used

It can also be informative to estimate the total water volume sent to the field during an irrigation event (and therefore removed from storage or from a water source). When water is applied to the field at a steady application rate over a given time, the total quantity of water applied per irrigation event is simply the total irrigation flow rate multiplied by the time of application.

Equation 12.5: Total water applied

$$V_{total} = Q_{total} \times T_{irrigation}$$

Where V_{total} is the volume applied (m^3), Q_{total} is the application rate of the irrigation network (m^3/s), and $T_{Irrigation}$ is the total time of application (in seconds).

This value, V_{total}, is the gross amount of water 'used' during the water application. Assuming flow rate measurements are made upstream of most in-field conveyance and distributions systems, the actual water applied to the plant root zone will be lower, due to water losses during conveyance and application. If the conveyance and application efficiencies of the irrigation network are known, they can be factored in to find the actual water applied to the soil around the crop.

Further reading – Measurement of irrigation water

Measurement of irrigation water, book chapter in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, by M.H. Ali (2010).

Measurement of water, book chapter in *Irrigation Water Management, Principles and Practice*. New Delhi: PHI Learning Private Limited, by D.K. Majumdar (2010).

Water Quality

Water quality parameters include a wide range of physical, chemical, and biological properties that make each water source unique. Water quality is not an absolute concept but a relative one: water quality needs only to correlate with its intended use. For example, river water that is considered to be high quality irrigation water may be poor quality drinking water because of its taste or color, factors which are irrelevant in irrigation but very important for drinking water.

The quality of blue water sources will vary over time and from season to season. River and lake water is normally at its highest quality during the rainy season, when the rains renew stream flow and dilute contaminant concentrations. During the dry season or other periods of low stream flow, surface water can become highly concentrated with contaminants. Groundwater often contains dissolved salts and silt in suspension, influenced by its movement through the soil.[6] Because low-quality irrigation water can harm the soil, inhibit plant growth and ultimately decrease the productivity of the land, it is important to know the quality of a blue water source before using it to irrigate fields.

A few factors are especially influential when determining the suitability of water sources for irrigation purposes: (i) salinity; (ii) chemical quality; and (iii) other contaminants specific to the water source.

Salinity

Salinity (total salt content) is the most important water quality parameter that determines its suitability for use in agriculture.[7] The application of water with high salinity to farm soils causes salts to build up over time, making it harder for plants to absorb soil moisture and causing long-term harm to the soil's productivity. It is common for irrigated farms in arid areas to experience soil salinity, rising shallow water tables, and waterlogging (see Chapter 2).

Salts accumulate in surface and groundwater through the natural weathering of rock and minerals in the environment. Salts are present in most blue water sources though they are generally more concentrated in groundwater.[8] Even seemingly small salt concentrations in the range of a few milligrams per liter can adversely affect crop growth and contaminate the farm environment if water use is sustained.

Beyond the absolute salt concentration, the *type* of salt compounds found in irrigation water is important in determining its suitability for irrigation.[9] There are many types of salts present in combination in saline water, and different salt compounds will vary in their impact on the water extraction capacity of plant roots. Sodium salts are most influential in this respect, so concentration values for these salts are often listed in water analyses alongside values for total salt concentrations. Excess sodium in irrigation water can lead to soil sodicity (see Chapter 2).[10]

Parameters used to quantify salt concentrations in irrigation water include TDS (total dissolved solids), EC (electrical conductivity), and SAR (sodium absorption ratio). Acceptable limits for these parameters are interconnected.

In some cases, and often in drinking water analysis, dissolved chloride ion concentration (Cl^-) is also used as a measure of salinity.[11] For more information about acceptable levels of salinity in irrigation water, and strategies for managing salinity, see the further reading box at the end of this section.

Water salinity testing is performed on-site using specialized sensors (such as a conductivity meter) or in a laboratory. Sometimes, soil testing services in agricultural regions are more easily accessible than water testing – in such cases measures of soil salinity can also be used to gauge the salinity levels of the water used in irrigation, though this strategy will be much less precise. Testing of water sources and/or soil should be pursued as soon as salinity is suspected. Mitigation measures for dealing with saline conditions can then be put in place before soil salinity/sodicity problems become severe.

Crops vary widely in their ability to tolerate saline conditions. Salt tolerance can also vary by growth stage: young plants in the germination and seedling stages tend to be most sensitive to salt. The relative salt tolerance of some major crop plants is outlined in Table 12.1. Note that this information is intended only as a general guideline, as actual tolerance levels will depend on soil quality, climate, crop strain, and other factors.

Table 12.1. Relative salt tolerance of some crops.[12]

Low tolerance	Medium tolerance	High tolerance
Beans	Broccoli	Sugarbeet
Peas	Brussel sprouts	Soybeans
Carrots	Cabbage	Beets (red)
Onions	Cauliflower	Squash (zucchini)
Parsnip	Celery	Cotton
Rice	Lettuce	Safflower
Strawberries	Spinach	Barley
Blackberry	Radishes	Oats
Boysenberry	Aubergine (eggplant)	Sorghum
Fruit trees:	Peppers	Wheat
Almonds	Tomato	Bermuda grass
Avocado	Cucumber	Fescue
Grapefruit	Melons	Harding grass
Orange	Winter squash, pumpkin	Perennial rye-grass
Lemon	Watermelon	Narrowleaf trefoil
Lime	Potato	Sudangrass
Pummelo	Sweet potato	Wheatgrass
Tangerine	Turnip	Wild rye
Apples	Broad bean (faba)	Date palms
Peaches	Groundnut (peanut)	Palm trees
Cherries	Flax	Pineapple
Pear	Casterbean	(Some) conifer trees
Apricot	Sunflower	Pomegranate
Plum/prune	Maize and sweet maize	Olives

Continued

Table 12.1. Continued.

Low tolerance	Medium tolerance	High tolerance
	Millet Lucerne (alfalfa) Clover Forage cowpea Foxtail Lovegrass Forage maize Orchardgrass Sesbania Sphaerophysa Big trefoil Common vetch Sugarcane Banana Grapes	Cowpea (non-forage)

Chemical quality

Water typically contains a vast number of different chemical constituents. Not all of these are harmful or relevant to water use in agriculture (although some may still be relevant for other uses of water). The concept of chemical water quality in the agricultural context refers primarily to specific ions that become toxic to plants when present in high relative concentrations. Some examples of chemical parameters that are relevant to water quality for agriculture include:

- pH – Water with both low pH (below 6) and high pH (above 8.5) can be harmful to plants and will affect the pH of soil.
- Boron – Plants require boron in small quantities, but an excess of it can be toxic. Some plants are more sensitive to boron toxicity, with effects noticed at concentrations as low as 1–2 mg/l.[13] High boron concentrations are most often encountered in the groundwater of arid regions.
- Sodium (Na) and chloride (Cl) ions – Independent of salinity, these ions are themselves toxic to plants in high concentrations. Chloride toxicity is common in irrigated soils, and can lead to plant injury, first visible in leaf tips.[14]
- Iron – Although iron is also required by the plant in small quantities, it is toxic in high concentrations and can clog irrigation networks. Water with high iron content is easily detected by red-brown stains on equipment or wall surfaces.[15]
- Alkalinity – Alkalinity is a measure of the water's capacity to neutralize acids, and is closely related to pH. If highly alkaline water is used in irrigation, it can cause soil pH to increase beyond manageable levels. Alkaline soil water will also reduce the effectiveness of fertilizers and agricultural chemicals.[16]
- Nitrate, potassium and phosphorous – These three elements, though essential to plant growth, can create environmental concerns if present in excessive

quantities. Nitrate in drinking water is linked to many illnesses and is a major cause of drinking water toxicity in agricultural areas.[17] When nutrients flow off of farm fields into rivers and lakes, they can cause *eutrophication*, which kills aquatic life.

- Heavy metals – Various heavy metals are readily taken up by certain plants: especially problematic are arsenic, copper, cobalt, nickel, zinc, and lead.

Chemical water quality is difficult to measure without specialized training or equipment. Unfortunately, most relevant water quality properties are invisible and need to be analyzed in the laboratory. In some places, simple test kits for pH, alkalinity, iron, arsenic and nitrite can be purchased for performing basic water tests.

Table 12.2 provides a selection of indicative values for irrigation water quality guidelines. These are sample values gathered from geographically diverse sources, so they should not be used as a coherent guideline. Irrigation water guidelines are contextual, and values may change significantly from place to place: national governments or agricultural extension offices may be able to provide local guideline documentation. Those concerned about salinity in irrigation water should consult the references in the further reading box at the end of this section.

Table 12.2. Sample irrigation water quality guidelines.[18]

Parameter	Recommendation	Unit[a]
Alkalinity[b]	1–100	ppm
Arsenic (As)[c]	< 0.2	ppm
Boron (B)[c]	< 2	ppm
Cadmium (Cd)[c]	< 0.1	ppm
Calcium (Ca^{++})[b]	40–120	ppm
Chloride (Cl^{-})[b]	< 140	ppm
Coliform (total)[c]	< 1000	n/100 ml
Electrical conductivity (EC)[c]	< 1200	μS/cm
pH[c]	6.0–8.5	–
Iron (Fe)[c]	1–2	ppm
Lead (Pb)[c]	< 0.1	ppm
Magnesium (Mg^{++})[b]	6–24	ppm
Mercury (Hg)[c]	< 0.01	ppm
Nitrate (NO_2)[c]	< 10	ppm as N_2
Phosphorous (P)[c]	< 15	ppm
Sulfate (SO_4)[c]	< 1000	ppm
Sodium (Na^{+})[b]	0–50	ppm
Total dissolved solids (TDS)[c]	< 2100	ppm
Zinc (Zn)[c]	< 10	ppm

[a]ppm, Parts per million (mg/l); n/100 ml, number of organisms per 100 ml; μS/cm, microsiemens per centimeter.

[b]Values from *Irrigation Water Guidelines* by Soil First Consulting (USA).[19]

[c]Standard of the Government of Bangladesh, 1997.[20]

Other contaminants specific to the water source

Depending on the specific geography of the farm, there is a chance that other, location-specific contaminants may affect the suitability of water for irrigation. These contaminants can be related to the geological conditions of the area, or can result from human activities occurring on or upstream of the farm.

It is useful to reflect on local conditions, both natural and human in origin, in order to identify potential contaminants that may be present in local water supplies. For instance, a farm located downstream from a municipality that releases untreated wastewater into surface water will need to be aware of the possible contamination of irrigation water by fecal bacteria, excess nutrients, and other potentially harmful wastewater constituents (see 'Wastewater' in the next section). A farm located in an area with arsenic-rich groundwater should test carefully to verify that the arsenic level of water used for irrigation does not reach toxic levels. Water trapped behind dams may have elevated levels of mercury, and surface water downstream of industrial developments can be contaminated with any number of chemical by-products, depending on the processes involved.

Further reading – Water quality for irrigation

Ayers, R.S. & Westcot, D.W., 1985. Water quality for agriculture. Available at: http://www.fao.org/docrep/003/T0234E/T0234E00.htm

Major Sources of Irrigation Water

Major sources of irrigation water include: (i) surface water; (ii) groundwater; (iii) wastewater; (iv) agricultural drainage water; and (v) harvested rainwater.

Surface water

Surface water is the most common source of irrigation water on farms fortunate enough to be within reach of rivers, lakes, or streams. The quantity of water available from these sources can seem inexhaustible, but irrigation has succeeded in draining some of the world's largest rivers and lakes, so caution should always be taken to avoid over-pumping surface water reserves. Water managers must also maintain minimum 'environmental flow' levels in surface water bodies to avoid damaging the ecological functions that keep the water source healthy.

The quality of surface water sources will depend on the natural characteristics of the watershed area as well as the activities of upstream water users.

Surface waters in dry climates tend to be high in sediment, especially in significantly eroded landscapes. Sediment can cause a loss of capacity in storage structures, as the settled sediment layer grows to occupy more and more space. Sediment can also block pumps and irrigation equipment.

In areas with clay-rich soils, rivers and lakes can be colored brown by suspended clay particles. While these are perhaps the most visible water characteristics, they are largely irrelevant to the water's suitability for agriculture. The most relevant water parameters, such as salinity and pathogenic microorganisms, are invisible to the naked eye and must be determined through testing.

River and lake water quality changes over time and within seasons. The highest quality water is usually found during rainy seasons. In coastal regions, the salinity of surface water bodies can vary according to flow volumes: low flows will increase the chances of saltwater intrusion into ground and surface waters.[21]

Groundwater

Of all the freshwater on earth, about 30% is stored as groundwater in aquifers of varying depths.[22] This is more than 100 times the water volume of all lakes and streams combined. Despite the large volumes available, groundwater use is not well developed in many resource-poor areas, including most notably sub-Saharan Africa where groundwater resources remain largely untapped. However, the natural recharge rate of groundwater aquifers is exceedingly slow, in the order of 0.1–3% per year.[23] Areas with widespread groundwater pumping for agriculture are prone to over-extraction, where groundwater is extracted faster than it can be recharged. Worldwide, it is estimated that groundwater is being depleted at nearly twice the rate of recharge, leading to falling water tables and associated social and environmental impacts.[24] Irrigated agriculture is the principal cause of groundwater over-extraction.[25]

Groundwater tends to be of better quality than surface water, owing to the filtration properties of the layers of subsoil. However, groundwater is more likely to be saline, because it moves slowly over layers of sand and bedrock that release salts into the water. This is especially true in arid environments, and in agricultural regions where groundwater pumping is commonplace. Coastal aquifers can also suffer from seawater intrusion, worsening the salt problem. In some areas, groundwater can also be high in arsenic, mercury, or other heavy metals.[26]

Wastewater

In peri-urban farms or areas located near urban sewerage infrastructure, wastewater represents an interesting and readily accessible source of irrigation water. Wastewater has the added benefit of being rich in nutrients that provide supplementary fertilization. However, wastewater can be more difficult to transport and manage than surface or groundwater because of its high solids content and unpredictable quality. Wastewater handling also carries potential health hazards for farm workers, neighbors and consumers.

The main health concern associated with untreated wastewater use in irrigation is the potential for transmission of pathogenic organisms from the water to the farmer or the consumer. Studies show that disease-causing organisms including helminth eggs (especially *Ascaris* spp. and *Trichuris* spp.), hookworm, viruses (including rotavirus) and bacterial vectors (including cholera) can indeed be spread in this manner.[27] The primary mode of transmission is direct contact with pathogen-rich wastewater, either through splashing or spraying during irrigation. The full health implications of irrigation with untreated wastewater are still poorly understood, yet millions of hectares of farmland worldwide depend on wastewater as their principal source of water and nutrients. Because direct contact is the easiest transmission route for pathogens, caution should always be exercised when handling untreated wastewater. The most basic precautions include wearing closed-toed shoes and gloves while working the land, and washing, cooking or boiling produce before consumption. Irrigation methods that deliver water directly to the soil surface without splashing the plant reduce the health hazard of wastewater use. If diarrheal diseases are frequent in farming families working with wastewater, additional measures may need to be taken to reduce the potential for infection by helminth eggs.[28]

When wastewater applied to the field percolates toward the water table, microbial contamination can spread to groundwater reserves and endanger drinking water supplies. If drinking water wells show signs of contamination within communities where wastewater irrigation is practiced, the practice should be terminated unless effective treatment can be arranged.

Wastewater flows that are likely to include industrial effluents can contain hazardous elements that are not commonly tested in surface water or groundwater. These include trace elements such as aluminum, fluoride and iron, and heavy metals such as arsenic, cadmium, chromium, copper, lead, zinc and mercury.[29] Soils watered with wastewater are typically high in heavy metals. These elements have the potential to build up in plant tissue and inhibit crop development. They can also accumulate in the edible portion of crops, causing health risks for the consumer.[30]

In cities, wastewater is normally treated using aerated lagoons, stabilization ponds, or more complex biological reactors. This treatment serves to reduce the organic content of the water and remove most suspended solids. However, not all cities provide wastewater treatment. Whenever possible, wastewater should be treated prior to reuse. Wastewater use in irrigation should also be combined with the use of 'normal' irrigation water (e.g. surface water or groundwater) by dilution or alternating applications – often, urban streams are already functionally similar to diluted wastewater.[31] Flushing with freshwater is important if the wastewater used has a high salt content.[32]

Wastewater is usually applied to the field through surface irrigation methods such as border or furrow irrigation. The solids content of wastewater can cause blockage in pumps and piping, so it should not be used in pressurized irrigation unless wastewater-specific equipment is available.

Further reading – Wastewater use in agriculture

Wastewater Irrigation and Health, produced by the International Development Research Centre (IDRC). Available at: http://www.iwmi.cgiar.org/Publications/Books/PDF/Wastewater_Irrigation_and_Health_book.pdf

Wastewater Treatment and Use in Agriculture, produced by the Food and Agriculture Organization of the United Nations (FAO). Available at: www.fao.org/docrep/t0551e/t0551e00.HTM

Agricultural drainage water

In areas where artificial drainage is practiced, it is natural to consider reusing drainage water to supplement irrigation. This is indeed a promising water conservation practice for areas with absolute water shortages. It can also be viewed as a pollutant control measure, since agricultural runoff water is a significant source of water pollution worldwide.

Agricultural drainage water can be considerably lower in quality than the original irrigation water applied. In its movement through the soil profile and drainage structures, it will have picked up salts, soluble fertilizer and pesticide residues, and other potentially harmful trace elements such as boron and sodium.[33] Drainage water tends to be highly concentrated, with up to ten times the salt content of the original irrigation water supplied.[34] Direct re-use of this water on the same fields would cause a steadily worsening buildup of salts and chemical elements in the soil, leading to long-term productivity losses and environmental hazards that could outweigh the benefit of the extra water supply.

The key to drainage water re-use is maintaining a favorable balance of salts and trace elements within the plant root zone. The most common salinity management tool is the application of additional water beyond the actual irrigation demand, in order to flush the soil and encourage leaching. When artificial drainage is practiced, leached salts end up in the drainage return water. If saline irrigation water is to be reused, it needs to be diluted with freshwater in order to keep salt concentrations below an acceptable value.[35]

Regardless of the source of irrigation water, it is important to set an upper limit of salt concentration that will allow the farmer to maintain a healthy salt balance within the soil layers of the root zone. Whenever irrigation water is saline, it will be necessary to provide occasional leaching-specific water applications to keep the soil healthy. It is much more efficient to supply the leaching requirement with freshwater low in salt content if this type of source is available.[36] Soil salinity is difficult to remediate once it has reached dangerous levels. For this reason, drainage water should only be re-used within an established salt management scheme.[37]

Further reading – Salinity management and drainage water use

Agricultural Drainage Water Management in Arid and Semi-arid Areas, produced by the FAO. Available at: www.fao.org/docrep/005/y4263e/y4263e00.HTM

Management of salt-affected soils, book chapter (pp. 271–325) in *Practices of Irrigation & On-farm Water Management*, Volume 2. New York: Springer, by M.H. Ali (2011).

Harvested rainwater

Harvested rainwater should be of excellent quality if properly stored. Rainwater in most areas is nearly pure, with the exception of some industrial areas where it can be lightly polluted. Rainwater collected as runoff from ground surfaces can however be loaded in sediment and other contaminants picked up on its path. Sediment buildup in reservoirs used for harvested rainwater is problematic. Sedimentation basins or physical-barrier-type sediment filters installed upstream of the reservoir can help reduce sediment loads within the storage reservoir.

Rainwater can also be harvested from rooftops and stored in large aboveground tanks. The quality of this water depends on roof surfaces and equipment management but should be sufficient for most domestic uses and the watering of kitchen gardens.

Further reading – Roof rainwater harvesting

Rainwater harvesting from rooftop catchments, in *Sourcebook of Alternative Technologies for Freshwater Augmentation in Latin America and the Caribbean*, produced by the United Nations Environment Programme (UNEP). Available at: www.unep.or.jp/ietc/Publications/techpublications/TechPub-8c/rooftop.asp

Moving Water to the Field

Moving water from source to field can require a great deal of energy. This represents one of the biggest obstacles to irrigation development on small farms. This section describes a few traditional, low-technology and low-cost options for moving water from surface or groundwater sources to the field. It is by no means exhaustive, but aims to cover some of the most long-standing water-moving techniques used by various cultures around the world.

Groundwater is accessed by constructing *wells* or *boreholes* dug to the depth of the most accessible or best quality aquifer present on the site. The design and maintenance of these structures is outside of the scope of this book, but some references for further reading on this subject are provided at the end of this section.

When river water is used for agriculture, the first step is often to create a temporary reservoir where water can build up before being diverted toward the field. This is accomplished through the construction of temporary or permanent water diversion structures, including concrete, sand or stone dams. Simple stone and sand dams are described in Chapter 7. Harvested runoff water is also stored in dams, ponds, or tanks. The form of storage area required will depend on the size and flow rate of the water body and diversion structures.

Water stored in wells, dams, ponds and reservoirs must then be diverted toward the field(s) for use in irrigation. If crop fields are located downhill from water storage sites, water can be directed there purely by the force of gravity. Most farms are not so lucky however, and must rely on water-lifting devices. Such devices can be powered by: (i) human power; (ii) animal power; or (iii) mechanical power. Several of the lifting devices described in this section are colloquially known as *pumps*, even though only mechanical lifting devices technically fit this description.[38]

The list below draws heavily from two resources: the Practical Action UK publication entitled *Human & Animal Powered Water-Lifting Devices for Irrigation* and the Netherlands Water Partnership (NWP) booklet entitled *Smart Water Solutions*. Both of these documents are available in full online. See the further reading box at the end of this section for full references.

Popular human-powered lifting devices

Hand pumps of various configurations can be used to lift water from shallow wells. These are typically purchased as pre-built well-top pump assemblies or constructed on site from PVC and metal parts. There are many variations on the conventional piston-pump model in use today, with a few of the most popular models currently the Afridev, India Mark II/III, and the Zimbabwe bush pump.[39] The long-term effectiveness of hand pumps is heavily dependent on good maintenance and the availability of spare parts: pre-built hand pumps that require imported spare parts are especially prone to failure.[40] Conventional piston-type hand pumps are only useful up to depths of 7 m, and they can produce only 24–36 l/min.[41] Deep-well (high lift) configurations can be used on depths of up to 50 m or more.[42] Hand pumps are generally more suited to drinking water supply than to agricultural use.

In the *swing basket* system, a basket (container) is fashioned out of locally available materials and affixed with four ropes. The basket is lowered into a shallow well or water reservoir and lifted by two people each holding two ends of rope. Water is lifted by swinging the basket from side to side while pulling on the ropes, and then discharged into a conveyance channel flowing toward the field. This system only works with water sources less than 1.2 m below the discharge point. Under good operation, the swing basket can provide a discharge rate of 60–80 l/min.[43]

The *don* (*dhone*) is a wooden or iron trough, closed at one end, attached to a central pivot point on the dry bank of a surface water source (Fig. 12.2). The other end of the 'see-saw'-like device is counterweighted. The operator pushes the trough section down into the water source then allows it to rise back up, driven by the power of the counterweight. The water from the trough then flows freely onto the banks and into a conveyance structure. The don system is best suited to lift water from depths of less than 1.5 m. Under those conditions it can provide between 80 l/min and 160 l/min.[44]

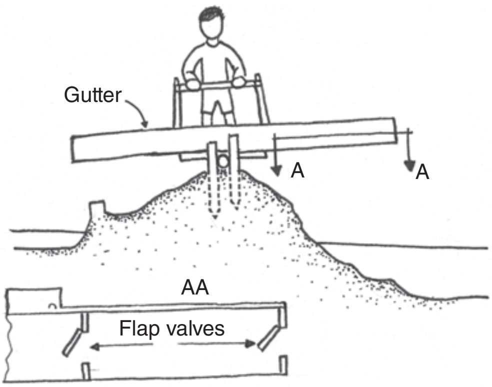

Fig. 12.2. The Don.[45]

The *shadouf* is a similar system which involves a bucket tied to one end of a hinged pole with a counterweight on its opposite end. The bucket is pushed into the water and allowed to lift out by the force of the counterweight. The water is then swung and emptied into a conveyance channel. A human operator can serve the role of counterweight in some designs. A sturdy shadouf system with a strong counterweight can lift water up to 4 m and provide discharge rates of about 60 l/min.[46]

The *paddle wheel* is mostly used in coastal areas to irrigate rice paddies. It consists of a radial array of 'paddles' centered on a horizontal axle and affixed to a frame that rests just below the surface of the water (Fig. 12.3). By walking on the paddles to make the wheel turn, the operator can lift the water from the source to a higher point where it is discharged into the conveyance network. The paddle wheel works best at shallow depths of less than a few meters and has a high discharge rate approaching 300 l/min.[47] A paddle wheel system can also be designed to be driven exclusively by the power of streamflow, such as in the traditional water wheel or *noria* system.[48]

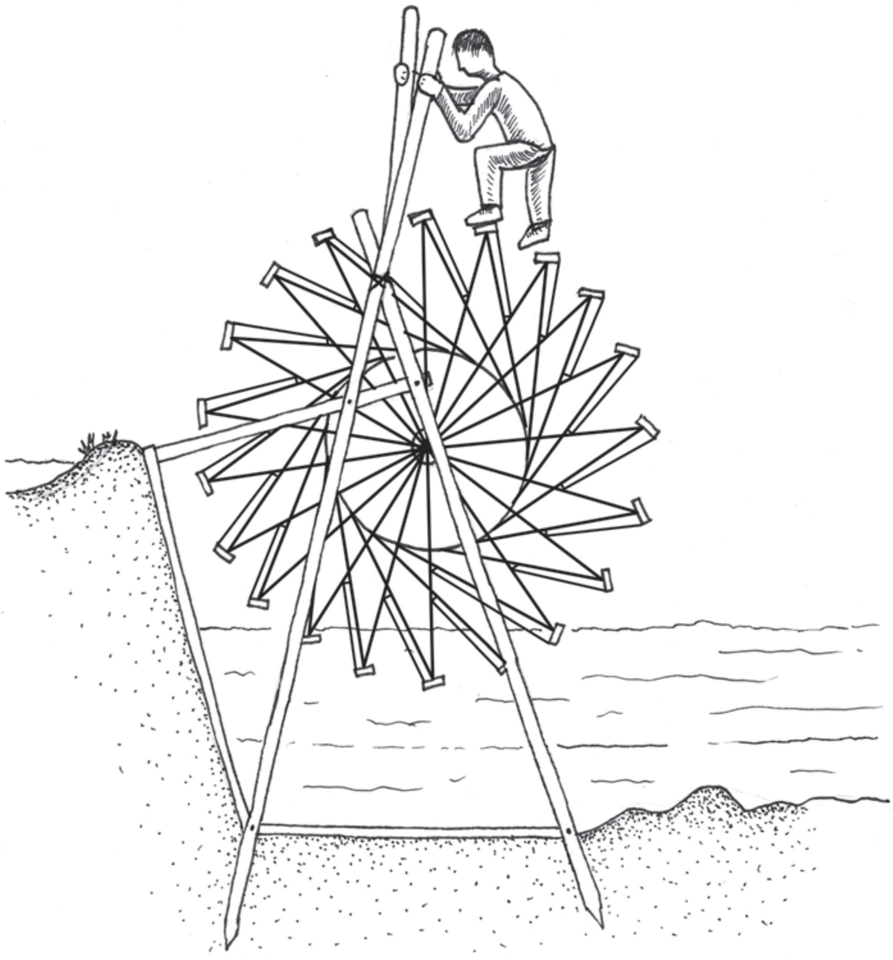

Fig. 12.3. The paddle wheel.[49]

The *treadle pump* is a human-powered water-lifting device that has been gaining in popularity since the late 1970s as a means for improving household incomes for poor farmers in Africa and Asia. The treadle pump has been marketed under the name 'Farmer's Friend' (*Krishak Bandhu*) in South Asia, and as 'Money Maker' in parts of Africa.[50] It is constructed from wood or bamboo poles and is powered by stepping on a pair of 'treadles' that in turn drive the action of a suction pump (Fig. 12.4). The treadle pump can be used to lift water as much as 7 m deep. It can be constructed using local materials and is inexpensive to build and operate. There are now over 1.3 million treadle pumps installed across South Asia, where they are sold at an average cost of US$20 each.[51]

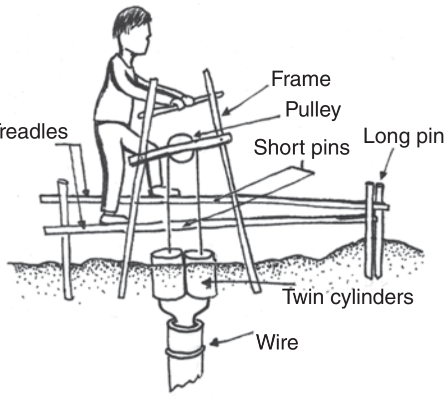

Fig. 12.4. The treadle pump.[52]

Traditional animal-powered lifting devices

The *Persian wheel* is constructed from a series of buckets (or containers) mounted on a wheel that extends down into a water source. The turning of the wheel pushes the water into the mounted buckets, which then lift water above the surface and discharge it into an awaiting reservoir or conveyance channel. The vertical water wheel is connected by a cog system to another wheel that is mounted horizontally above a flat ground surface (Fig. 12.5). This wheel is connected by means of a horizontal pole to the yoke of one or more draught animals who move in circles around the wheel to power the device. The Persian wheel is efficient at depths of up to 20 m, but works best at depths of less than 8 m. At that depth, it can be counted on to provide a discharge rate of 160–170 l/min.[53] Similar lifting devices based on this principle include the *zasaffa* or *jhallar*, and the scoop-wheeled *sakia*, *tympanum* or *tablia*.[54]

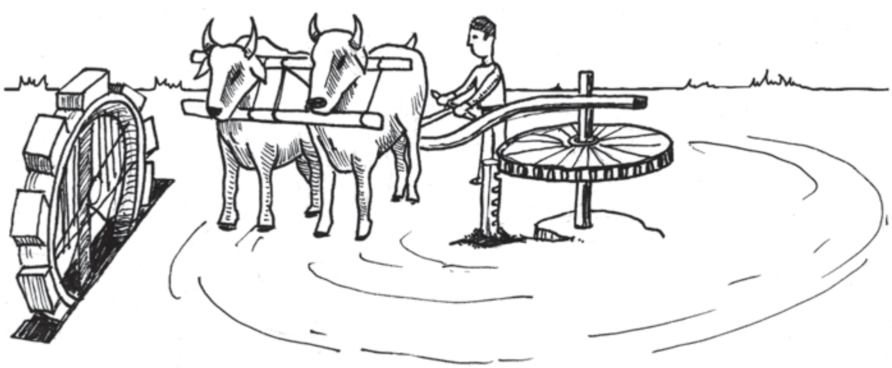

Fig. 12.5. The Persian wheel.[55]

The *rope-and-bucket* system for lifting groundwater can be driven by humans, but is much more efficient under animal power. This simple system involves lowering a bucket or other container on a rope into a wide shallow well, up to a depth of 50 m. The rope is pivoted on a pulley device and is pulled up by an animal (or person) as it moves away from the well. A shallow slope of 5–10% is typically created in the ground leading away from the well, to facilitate the job of lifting the water. The bucket can be rigged to tip itself at the top of its trajectory, or self-emptying funnel-shaped containers can be used, as in the *mohte* system.[56]

A *chain pump* or *rope pump* is similar in principle to the Persian wheel in that it is based on the rotating motion of a continuous chain through a low surface-water body or groundwater well (Fig. 12.6). The chain is fitted with horizontal discs set at regular intervals which pass through the free water surface at the lower part of the wheel's rotation. A pipe of about the same diameter as the discs is installed to extend from the ground to beneath the surface of the water, and as the chain and discs are pulled through this pipe, water is trapped and lifted to the surface. Chain pumps are relatively easy to maintain and can be built from a variety of available materials, including ropes, pipes, or old mechanical parts. They can be used to pump groundwater or surface water from great depths, though most are not more than 35 m deep. The wheel system can be turned by hand or adapted for animal traction. Under animal power, the chain pump can discharge water at 40–60 l/min. A variation of the chain pump known as the 'dragon spine pump' is mounted on a slight angle to reduce the lifting power required. These are used at shallow depths not exceeding 6 m.[57]

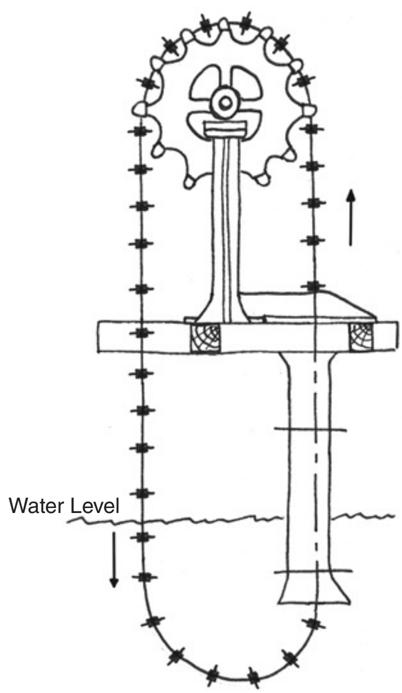

Fig. 12.6. A chain pump.[58]

Basic mechanically-powered lifting devices

Mechanically-powered lifting devices require an external source of power and are collectively known as *pumps*. Pumps used in irrigation can be powered by diesel fuel, gasoline, electricity, or even solar energy. The 5 hp (horsepower) diesel pump is considered industry standard for groundwater pumping, but newer 2.5 hp pumps have been shown to produce the same results with less fuel.[59,60] Many types of water pump are used in agricultural applications, including both surface-mounted and submersible pumps of various formats. Mechanical pumps are usually chosen based on the type of energy source available and local market availability. They are among the most expensive type of water-lifting devices available and can be prone to failure because of the need for specialized maintenance and/or hard-to-find spare parts.

Pumping water from deep wells (below 7 m) requires more investment still. Deep-well pumping requires generator pump sets or long-shaft diesel pumps that can cost hundreds of dollars.[61] Alternatively, deep-well rope or chain pumps (as described above) can be motorized with the help of an electric motor or gas engine. This option can be considerably cheaper than deep-well pumps in many cases.[62]

Further reading – Water moving

Human & Animal Powered Water-Lifting Devices for Irrigation, booklet produced by Practical Action UK. Available at: http://answers.practicalaction.org/our-resources/item/human-animal-powered-water-lifting-devices-for-irrigation

Smart Water Solutions: Examples of Innovative, Low-cost Technologies for Wells, Pumps, Storage, Irrigation and Water Treatment, produced by the Netherlands Water Partnership (NWP). Available at: www.ircwash.org/sites/default/files/NWP-2006-Smartwater.pdf

Water Lifting Devices, booklet produced by the FAO. Available at: www.fao.org/docrep/010/ah810e/AH810E05.htm

References

1 Stockle, C.O., 2001. *Environmental Impact of Irrigation: a Review*. Pullman, Washington: State of Washington Water Research Center, p. 4.

2 Barron, J. & Salas, J.C., 2009. *Rainwater Harvesting: a Lifeline for Human Well-being*. Nairobi: UNEP/Stockholm Environment Institute (SEI), p. 9.

3 Adapted from Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 224.

4 Ibid.

5 Loosely adapted from Ali, M.H., 2010. Measurement of irrigation water, in *Fundamentals of Irrigation and On-farm Water Management,* Volume 1. New York: Springer, pp. 453–487.

6 Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 365.

7 Ayers, R.S. & Westcot, D.W., 1985. Water quality for agriculture. Available at: http://www.fao.org/docrep/003/T0234E/T0234E00.htm [Accessed March 6, 2013].

[8] Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 366.

[9] Ayers, R.S. & Westcot, D.W., 1985. Water quality for agriculture. Available at: http://www.fao.org/docrep/003/T0234E/T0234E00.htm [Accessed March 6, 2013].

[10] Brouwer, C. *et al*., 1985. *Irrigation Water Management: Introduction to Irrigation*. Rome: FAO.

[11] Ali, M.H., 2010. Water: an element of irrigation, in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, pp. 271–329.

[12] Adapted from Allen, R.G. *et al*., 1998. Crop evapotranspiration – guidelines for computing crop water requirements. *fao.org*. Available at: www.fao.org/docrep/X0490E/x0490e00.htm [Accessed December 6, 2012].

[13] Ayers, R.S. & Westcot, D.W., 1985. Water quality for agriculture. Available at: http://www.fao.org/docrep/003/T0234E/T0234E00.htm [Accessed March 6, 2013].

[14] Ibid.

[15] Soil First Consulting, unknown date. *Irrigation Water Guidelines*. *earthworksturf.com*. Available at: http://www.earthworksturf.com/pdf/soiltest/Irrigation_%20Water_Guidelines.pdf [Accessed May 16, 2013].

[16] Ibid. p. 1.

[17] Ali, M.H., 2010. Water: an element of irrigation, in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, pp. 271–329.

[18] Adapted from: (i) Soil First Consulting, unknown date. *Irrigation Water Guidelines*. *earthworksturf.com*. Available at: http://www.earthworksturf.com/pdf/soiltest/Irrigation_%20Water_Guidelines.pdf [Accessed May 16, 2013]; and (ii) Ali, M.H., 2010. Water: an element of irrigation, in *Fundamentals of Irrigation and On-farm Water Management* Volume 1. New York: Springer, p. 291.

[19] Soil First Consulting, unknown date. *Irrigation Water Guidelines*. *earthworksturf.com*. Available at: http://www.earthworksturf.com/pdf/soiltest/Irrigation_%20Water_Guidelines.pdf [Accessed May 16, 2013].

[20] Ali, M.H., 2010. Water: an element of irrigation, in *Fundamentals of Irrigation and On-farm Water Management*, Volume 1. New York: Springer, p. 291.

[21] Majumdar, D.K., 2010. *Irrigation Water Management*. New Delhi: PHI Learning Private Limited, p. 374.

[22] United States Geological Survey (USGS). Where is Earth's water? USGS Water-Science School. *water. usgs.gov*. Available at: http://water.usgs.gov/edu/earthwherewater.html [Accessed November 4, 2015].

[23] Garcia-Tejero, I. *et al*., 2011. *Water and Sustainable Agriculture*. Dordrecht, The Netherlands: Springer, p. 34.

[24] Ibid.

[25] Shah, T. *et al*., 2012. *The Global Groundwater Situation: Overview of Opportunities and Challenges*. Colombo: International Water Management Institute (IWMI).

[26] Ibid.

[27] Pescod, M.B., 1992. Wastewater treatment and use in agriculture. *fao.org*. Available at: http://www.fao.org/docrep/t0551e/t0551e00.HTM [Accessed March 5, 2013].

[28] Ibid.

[29] Ibid.

[30] Ibid.

[31] Drechsel, P. *et al*., 2006. *Informal Irrigation in Urban West Africa: An Overview*. Colombo: IWMI.

[32] Pescod, M.B., 1992. Wastewater treatment and use in agriculture. *fao.org*. Available at: http://www.fao.org/docrep/t0551e/t0551e00.HTM [Accessed March 5, 2013].

[33] Tanji, K.K. & Kielen, N.C., 2002. Agricultural drainage water management in arid and semi-arid areas. *FAO Irrigation and Drainage Papers*, (61), p. 205.

[34] Ibid.
[35] Ibid.
[36] Ayers, R.S. & Westcot, D.W., 1985. Water quality for agriculture. Available at: http://www.fao.org/docrep/003/T0234E/T0234E00.htm [Accessed March 6, 2013].
[37] Tanji, K.K. & Kielen, N.C., 2002. Agricultural drainage water management in arid and semi-arid areas. *FAO Irrigation and Drainage Papers*, (61), p. 205.
[38] Fraenkel, P.L., 1986. Water lifting devices. *fao.org*. Available at: http://www.fao.org/docrep/010/ah810e/AH810E05.htm [Accessed August 31, 2015].
[39] Baumann, E. & Furey, S., 2013. *How Three Handpumps Revolutionised Rural Water Supplies*. St. Gallen, Switzerland: Rural Water Supply Network (RWSN).
[40] Netherlands Water Partnership (NWP), 2006. *Smart Water Solutions*. The Hague, The Netherlands: NWP.
[41] Practical Action, 2008. *Human & Animal Powered Water-Lifting Devices for Irrigation*. Rugby, UK: Practical Action Publishing.
[42] Baumann, E. & Furey, S., 2013. *How Three Handpumps Revolutionised Rural Water Supplies*. St. Gallen, Switzerland: RWSN.
[43] Practical Action, 2008. *Human & Animal Powered Water-Lifting Devices for Irrigation*. Rugby, UK: Practical Action Publishing.
[44] Ibid.
[45] Adapted with permission from Ibid.
[46] Ibid.
[47] Ibid.
[48] Fraenkel, P.L., 1986. Water lifting devices. *fao.org*. Available at: http://www.fao.org/docrep/010/ah810e/AH810E05.htm [Accessed August 31, 2015].
[49] Adapted with permission from Fraenkel, P.L., 1986. Water lifting devices. *fao.org*. Available at: http://www.fao.org/docrep/010/ah810e/AH810E05.htm [Accessed August 31, 2015].
[50] Shah, T. *et al*., 2012. *The Global Groundwater Situation: Overview of Opportunities and Challenges*. Colombo: IWMI.
[51] NWP, 2006. *Smart Water Solutions*. The Hague, The Netherlands: NWP.
[52] Adapted with permission from Practical Action, 2008. *Human & Animal Powered Water-Lifting Devices for Irrigation*. Rugby, UK: Practical Action Publishing.
[53] Ibid.
[54] Fraenkel, P.L., 1986. Water lifting devices. *fao.org*. Available at: http://www.fao.org/docrep/010/ah810e/AH810E05.htm [Accessed August 31, 2015].
[55] Adapted with permission from Practical Action, 2008. *Human & Animal Powered Water-Lifting Devices for Irrigation*. Rugby, UK: Practical Action Publishing.
[56] Ibid.
[57] Ibid.
[58] Adapted with permission from Practical Action, 2008. *Human & Animal Powered Water-Lifting Devices for Irrigation*. Rugby, UK: Practical Action Publishing.
[59] NWP, 2006. *Smart Water Solutions*. The Hague, The Netherlands: NWP.
[60] Shah, T. *et al*., 2012. *The Global Groundwater Situation: Overview of Opportunities and Challenges*. Colombo: IWMI.
[61] NWP, 2006. *Smart Water Solutions*. The Hague, The Netherlands: NWP.
[62] Ibid.

Summary of Key Points

- Dry spells during the growing season, and not total rainfall deficits or droughts, are the principal cause of water deficit on most rainfed farms.
- The impact of dry spells on crop yields can be mitigated by adopting soil and water conservation practices, harvesting rainfall, applying supplemental irrigation, and/or practicing conservation agriculture.
- In many dryland areas, over half of the rain that falls is not captured by the soil but is lost as runoff, evaporation, deep percolation, and evaporation.
- The capacity of field soils to hold water is closely related to organic matter content and soil type.
- Soil organic matter content can be enhanced by providing soil cover, recycling plant residues into the soil, and planting several varieties of crop.
- Cover crops and green manures cover the soil while acting as natural fertilizer.
- Rainwater runoff can be beneficially harvested to provide additional water inputs.
- Mixed cropping systems that incorporate different species and varieties are ultimately more productive and provide better water productivity.
- Conservation agriculture is a set of practices that promote healthy soils, require less labor, and foster resilience to climate variability.
- Irrigation is most efficient when applied sparingly at critical points in the plant's life cycle to mitigate the water stress impact of dry spells.
- Surface irrigation is a low-cost way to apply irrigation water, but also the least efficient because water losses are high.
- The timing of irrigation is very important – knowing the feel of the soil and the plant can help to predict the best times to irrigate.
- Applying water preferentially during critical growth stages will have the biggest impact on yields.

- In areas with shallow groundwater or poor drainage, artificial drainage can be necessary to maintain a healthy soil.
- Irrigation water that is high in salts or trace elements can harm the soil and the crop.
- Agricultural practices that involve only one crop and that leave soil bare between rows lead to water loss and soil degradation.
- Biodiversity (presence of many species of plants, animals, and insects) is vital to the health of the farm system.

Index

Note: bold page numbers indicate figures and tables.

Sustainable Water Management in Smallholder Farming

Theory and Practice

Sara Finley

Water is critical to all human activities, but access to this crucial resource is increasingly limited by competition and the effects of climate change. In agriculture, water management is key to ensuring good and sustained crop yields, maintaining soil health, and safeguarding the long-term viability of the land.

Water management is especially challenging on smallholder farms in resource-poor areas, which tend to be primarily rainfed and thus highly dependent on unreliable rainfall patterns. Sustainable practices can help farmers promote the development of soils, plants and field surfaces to allow maximum retention of water between rains, and encourage the efficient use of each drop of water applied as irrigation. Using simplified concepts and easy-to-understand language, this book:

- outlines the theoretical underpinnings of sustainable water management in agriculture
- introduces a range of beneficial practices, including the enhancement of soil water retention, water loss reduction, rainwater harvesting, conservation agriculture, and small-scale irrigation
- provides schematic diagrams and resources for further reading to help readers put theory into practice

Especially useful for farmers' groups, agricultural extension workers, NGOs, students and researchers working with farmers in dryland areas, this comprehensive yet concise book is a practical and accessible resource for anyone interested in sustainable water management.

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