Green Water Management Handbook

Rainwater harvesting for agricultural production and ecological sustainability

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Edited by:

Maimbo M. Malesu

Alex R, Oduor

Orodi J. Odhiambo

Contributors:

Maimbo M. Malesu

Alex R. Oduor

Orodi J. Odhiambo

Ephraim M. Senkondo

Ayub Shaka

Peter Okoth

Anna Mutinda

Joyce S. Musiwa

John Mutua

World Agroforestry Centre

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Editor of Water Management Series of Publications,
Alex R. Oduor, Programme Officer
World Agroforestry Centre, Eastern Africa Region

Editor of ICRAF Global Series
George Obanyi, Editor
World Agroforestry Centre, Eastern Africa Region.

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Logitech Ltd
P.O. Box 1003 00100
Nairobi, Kenya

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List of Synonyms

ACZ	Agro-climatic zone
AfDB	African Development Bank
AMCOW	African Ministerial Council on Water
AWTF	African Water Task Force
ASAL	Arid and Semi-Arid Lands
CAADP	Comprehensive Africa Agriculture Programme
ECA	Economic Commission for Africa
ET	Evapotranspiration
FAO	Food and Agricultural Organization of the United Nations
GIS	Geographical Information System
GPS	Geographic Positioning System
GWP	Global Water Partnership
GWP/AP	Global Water Partnership-Associated Programme
ICRAF	International Centre for Research in Agroforestry / World Agroforestry Centre
IWRM	Integrated Water Resource Management
MDG	Millennium Development Goals
NEPAD	New Partnership for Africa's Development
NGO	Non Governmental Organization
RELMA	Regional Land Management Unit
RWH	Rainwater Harvesting
SEARNET	South and East Africa Rainwater harvesting Network
UNEP	United Nations Environmental Programme
WSSD	World Summit for Sustainable Development
SOTER	Soil Terrain Database

Preface

The water cycle is partitioned into blue and green flows. Green water constitutes 65% of the total precipitation at global scale and blue water the rest. Green water is used in forests, grasslands, wetlands and croplands, while blue water sustains ecosystems.

Owing to the visibility of blue water as it flows into surface and underground reservoirs as runoff or base flow respectively, most governments and policy institutions have focused on it for planning purposes while neglecting the green water fluxes. This has created an impression of water scarcity, especially in Africa. For instance, the United Nations Economic Commission for Africa (UNECA) projects that 14 countries in Africa will suffer from water stress and scarcity by the year 2025.

Already, the competition for the scarce water resource is intense in many places, with river basins not having enough to meet all demands. Lack of water is a major constraint to food production. According to the Comprehensive Assessment report, it takes up 70% of freshwater.

However, inclusion of the green water potential in the hydrologic equation changes the picture. A study by World Agroforestry and UNEP on mapping of water harvesting potential for Africa and nine selected countries shows that the continent receives around 24,000 km^3 of rainwater, 75% of which can be used to support the livelihoods of millions, mainly through production of food, tree and livestock products. Africa is thus not physically water scarce. The problem is more of an economic nature owing to inadequate capacity and investments in infrastructure to manage water, including its storage. This inadequacy has reduced access to available water, jeopardizing efforts to improve food production.

This handbook highlights the principles and technologies that can be used to harness the huge untapped potential of rainwater. Instead of a stereotyped view focusing only on rivers and groundwater, the book directs readers in recognizing rain as the ultimate source of water for food production and other uses in rural economies across Africa.

The book gives attention to climatological aspect of rainfall as a key component in the design of water harvesting technologies. The handbook looks at factors that influence rainfall and the effect of climate change. Also covered are technical options for rainwater management for crops, livestock and environmental systems. Other topics include economic evaluation of rainwater and sustainability of water resources. There is also a section dedicated to extension approaches, gender and policy considerations.

Finally, the handbook is based on practical experiences of work gained by members of the Southern and Eastern Africa Rainwater Network (SearNet, www.searnet.org), many of who contributed content for the various chapters. The participatory approach to developing this book makes it a useful reference for trainers and others interested in the practical application of water harvesting technologies in the field.

Dr. Dennis Garrity
Director General
World Agroforestry Centre

Acknowledgement

This document is inspired by the desire of SearNet members to be custodians of reference material for green water management which they can use in building the capacity of rainwater harvesting practitioners in the East and Southern Africa sub-continent. A workshop organized in July 2003 deliberated on the contents and potential authorship of the handbook. Although it took five years to finally accomplish preparation of the draft, the Secretariat kept pace in upraising the document with up-to-date technological status of rainwater harvesting for agriculture.

In lieu of the above, the Secretariat is grateful to all the participants of the Machakos workshop in Kenya, who contributed immensely in developing the outline for this handbook. The authors also wish to recognize institutions or persons who delivered photographs, case studies, comments and advice that were crucial in enriching the handbook.

Compilation of this handbook wouldn't have been possible were it not for the endeavour put in by Naomi Njeri, the Programme Assistant of the Global Water Partnership Associated Programme.

Finally, lots of gratitude go to the Netherlands Ministry of Foreign Affairs for facilitating the printing and distribution of this publication which forms a key reference material for the upscaling programmes and projects across Africa.

Chapter 1

Introduction

1.1 General overview

Since the dawn of civilization the human race has recognized the importance of rainfall as the primary source of water to sustain life. Unlike many of the world's resources, water is renewable (Table 1). Water evaporates from the oceans, seas and land into the atmosphere as vapour (Fig. 1, Box 1). From the atmosphere, rain falls on the land, and eventually finds its way back to the oceans. The volume of water on the move in this way has been estimated as 520,000 km^3 (cubic kilometres) a year, of which 412,000 km^3 returns to the oceans as direct precipitation and 108,000 km^3 falls on land.

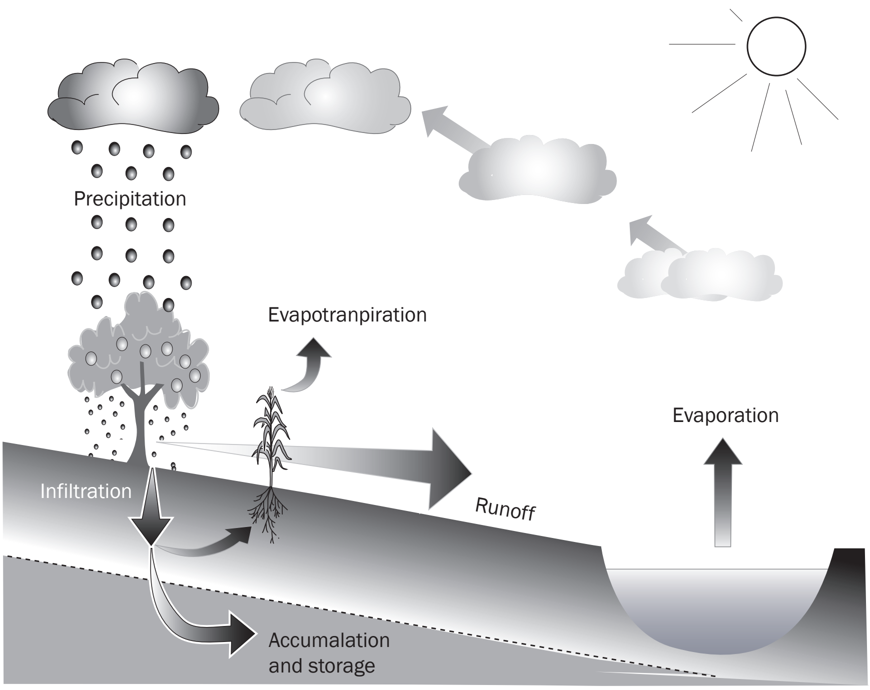


Figure 1: *The hydrological cycle*

Rainfall that falls on land either seeps into the ground or becomes runoff, flowing into rivers and lakes. What happens to the rain after it falls depends on many factors such as:

- *The rate of rainfall*
  A lot of rain in a short period creates large amounts of surface water that tend to run off the land into streams rather than soak into the ground.

- *The topography of the land*
  Topography is the lie of the land—the hills, valleys, mountains and canyons. Rain falling on land drains downhill until it flows into streams, accumulates in depressions such as lakes, or soaks into the ground.

- *The type of soil*
  In dense clay soils, rainwater takes a long time to infiltrate. By contrast, where soils are sandy, such as in deserts, rain is quickly absorbed, at least initially.

- *The density of vegetation cover*
  It has long been accepted that plant growth helps prevent erosion caused by runoff. Hills without vegetation are often dissected by gullies eroded by running water. Plant cover slows water flow and thus helps to prevent soil erosion.

- *Urbanization*
  City authorities spend a lot of money on infrastructure to remove water from built-up areas, such as roads, pavements and parking lots. Runoff from these impervious areas exceeds the capacity of creeks and streams and these watercourses overflow and flood adjacent areas.

Box 1. Forms of water

Water continually changes its form—from water vapour to liquid water and ice—as it moves through the hydrological cycle. The earth is pretty much a ‘closed system’, similar to a terrarium. This means that the earth neither gains, nor loses, much material, including water. Although some material, such as meteors, is captured by earth, very little escapes into outer space. This is certainly true of water. This means that the water that existed millions of years ago is the same water that exists at present. It is entirely possible that the water you drank for lunch was once used by Mama Atieno to give her baby a bath.

Precipitation on land supports all the earth’s natural vegetation and rainfed crops. Each year, river runoff supplies 37,000 km^3 for irrigation and domestic needs.

The proportion of river runoff that is intercepted and used is small: about 9%, or an estimated 3,300 km^3. In high rainfall areas, much rain runs off into rivers or as floods and cannot be used. The global average annual precipitation on terrestrial areas is 725 mm, but there are very wide geographical variations—from zero in deserts to over 5,000 mm in the tropics. In low rainfall areas, most of the rain often evaporates. Very little reaches drainage channels and watercourses to become usable water. Worldwide, annual runoff into river systems is about 35% of precipitation. In drier parts of the world, annual runoff into river systems is frequently less than 25%, and there are many river systems where it is only 3–4%. Collecting runoff near its source reduces losses considerably. Where this can be done, multiple collection systems in small catchments can save more water than a single collection system in a large catchment.

Table 1: *Renewal period for water resources*

Water in the hydrosphere	Period of renewal
Oceans	2,500 years
Groundwater	1,400 years
Polar ice	9,700 years
Mountain glaciers	1,600 years
Ice in the permafrost zone	10,000 years
Lakes	17 years
Bogs	5 years
Soil moisture	1 year
Channel network	16 days
Atmospheric moisture	8 days
Biological water	Several hours

1.2 Water resources in Africa

Surface water resources

Overall, Africa has less surface water and a higher evaporation rate per unit area than other regions of the world (Fig. 2). Seasonal flow in most African rivers varies considerably, with the notable exception of the Zaire River. Surface water is unevenly distributed over the continent. The Zaire basin, extending over 16% of Sub-Saharan Africa (SSA), has 55% of the continent's mean annual discharge. Only a few major rivers, including the Nile, flow through the drought-prone areas of the Sudano-Sahelian region that includes Somalia, limiting irrigation and restricting agriculture to rainfed crops.

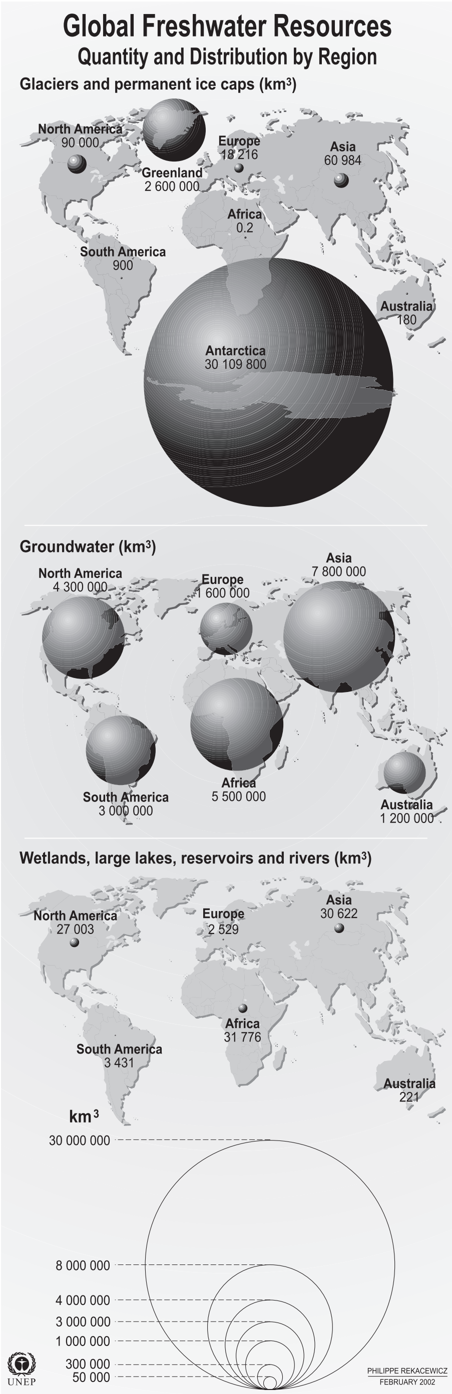
The proportion of rainfall captured in rivers varies considerably. In the Saharan region, there are neither surface runoffs, nor surface water resources. In the Sudano-Sahelian region, runoff averages up to 10% of rainfall, whereas in the wet tropical highlands of Ethiopia, runoff is currently more than 20% of rainfall.

Groundwater resources

Groundwater comprises an estimated 20% of total water resources of Africa. High-yielding aquifers underlie about 10% of the continent. The occurrence of groundwater depends on local and regional climatic and geologic conditions.

The amount of water that infiltrates into groundwater aquifers each year depends on the amount and annual distribution of rain, and the evaporation rate. Rainfall and evaporation in turn depend on latitude, altitude and temperature. For areas where rainfall is less than 250 mm, the amount of infiltration closely corresponds with rainfall intensity. In areas where rainfall is between 250 mm and 1,000 mm, potential evapotranspiration determines the amount of infiltration. In areas where rainfall exceeds 1,000 mm, a substantial proportion of rainfall usually infiltrates the ground.

The water-bearing formations underlying over half the continent consist of fractured, altered, granitic, metamorphic and volcanic rocks. These formations contain small, discontinuous aquifers with low recharge rates. In the great sedimentary basins in the interior of Africa, groundwater yields from thick and extensive formations can be important, but aquifers are often at great depth and thus groundwater is costly to extract. In the deserts of North Africa, aquifers are often artesian. Recharge to these artesian aquifers is, however, uncertain and well yields tend to fall off. Abundant shallow groundwater underlies alluvial riverbeds where runoff infiltrates. Many coastal deltas and plains of Africa overlie sedimentary basins with important but shallow permeable horizons. Where these coastal aquifers have been over-exploited, they have been contaminated by intrusions of saline water.



Note: Estimates refer to standing volumes of freshwater.
Source: Igor A. Shiklomanov, State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational, Scientific and Cultural Organisation (UNESCO, Paris), 1999; World Meteorological Organisation (WMO); International Council of Scientific Unions (ICSU); World Glacier Monitoring Service (WGMS); United States Geological Survey (USGS).

Figure 2: *Global freshwater resources: quantity and distribution by region*

Falkerman *et al.* (1990) proposed that 1700 m^3 per capita per year is the minimum amount of water required to maintain an adequate quality of life. Based on this water-scarcity index, three out of ten SearNet countries (Botswana, Ethiopia, Kenya, Malawi, Rwanda, Swaziland, Tanzania, Uganda, Zambia, Zimbabwe) were water-scarce in 1990; this number will increase to four in 2025, and five by 2050 (Table 2).

Given the limited availability and vital importance of water, efficient and effective use of water resources is a necessity for the sustainable economic and social development of SearNet countries.

The need to broaden the approach to managing water resources will increase as populations grow in water-scarce regions and as migration from rural areas to urban centres continues. Projected increases in water withdrawal may trigger massive ecosystem collapses and land degradation, leading to social unrest, especially in downstream coastal areas.

Table 2: *Renewable and per capita freshwater availability in SearNet countries (shading indicates water scarcity)*

Country	Total annual renewable freshwater available (BCM)	Per capita water availability, 1990 (m^3)	Per capita water availability, 2025 (m^3)	Per capita water availability, 2050 (m^3)
Botswana	18	14,107	6,401	5,321
Ethiopia	110	2,320	947	690
Kenya	15	635	248	190
Malawi	9	961	421	305
Rwanda	6.3	902	432	351
Swaziland	6.96	9,355	4,543	3,854
Tanzania	76	2,969	1,264	962
Uganda	66	3,677	1,519	1,134
Zambia	96	11,779	5,264	4,120
Zimbabwe	23	2,323	1,275	1,061

Source: (Oduor and Maimbo, 2006). Shading represents water scarcity.

Around 70% of agricultural land in the world's savannas (often defined as drylands) is degraded. In these areas, drought and desertification threaten the livelihoods of over one billion people. In addition, authorities pay little attention to reducing and preventing water pollution. Projected increases in water withdrawal will also exacerbate the growing problem of deteriorating water quality.

Conflicts between competing water users, between land use and terrestrial ecosystems upstream and water use and aquatic ecosystems downstream, are becoming more frequent and threaten both the internal and external security of many nations. These trends mean that successful socioeconomic development will depend on managing increasing competition for water, water pollution and demand for water-dependent raw materials. Climate change—bringing uncertainty and surprise, more frequent dry spells, droughts and floods—will exacerbate this daunting task.

1.3 Uses of water

Freshwater is critical to human survival and environmental sustainability. Water supports human existence, is essential for producing food and energy, and is important for transportation.

Population growth, development aspirations and a growing recognition of the importance of ecosystem support services, are raising awareness that water is a key factor in socioeconomic development. Water is of vital importance in, for example, industry, forestry, fibre production and fisheries. Upstream land use and water management determine the volume, patterns of flow and quality of water for downstream use. So, upstream forestry, rainfed farming and grazing (all of which consume freshwater) determine water availability downstream.

Water for generating energy

Hydropower plants capture the energy of falling water to generate electricity. Turbines convert the kinetic energy of falling water into mechanical energy. Then, generators convert mechanical energy produced by turbines into electrical energy.

Hydropower plants range in size from 'micro-hydros' that power only a few homes to giant plants, such as on the Hoover Dam, that provide electricity for millions of people.

- Worldwide, about 20% of all electricity is generated by hydropower.
- Hydropower plants can respond quickly to fluctuations in consumer demand and to emergency energy needs.

Water for ecological sustainability

Freshwater ecosystems support fisheries and other aquatic biodiversity, provide important regulating services, and are an essential component of the freshwater cycle. Because they retain water, wetlands, rivers, lakes and reservoirs help mitigate flooding. In reality, all freshwater ecosystem functions within a watershed are interlinked (Melnick *et al.*, 2005).

Sustaining aquatic ecological functions in rivers, lakes, riparian zones and estuaries requires huge volumes of water. Fresh water sustains biomass growth in terrestrial ecosystems, and provides key ecological services—maintaining biodiversity, sequestering carbon and combating desertification. However, managing competing demands for water resources is becoming increasingly complicated. Fortunately, as water contamination escalates, water users are becoming more aware of the links between upstream pollution and downstream water quality.

Water for health

Water makes up two-thirds of the human body. It is a key component of all tissues and organs, and allows them to regulate their volume and internal osmotic pressure.

Absorbing water through roots and maintaining water balance are critical for plant growth. In the human body, different tissues and organs have different water contents and many pathological processes are reflected in altered water content which can be observed using magnetic resonance imaging techniques (Falkerman, 2005).

Safe drinking water to maintain healthy body functions is therefore the birthright of all humankind, as much so as clean air. Yet most of the world's population does not have access to safe drinking water. Safe drinking water is of paramount concern because 75% of all diseases in developing countries are due to polluted drinking water. Polluted water or a lack of water also leads to other diseases, including:

- cholera (as a lack of water leads to a lack of sanitation facilities and unhygienic living conditions);
- malaria (as stagnant water bodies provide breeding grounds for mosquitoes);
- bilharzia (as water moving at low velocities, such as that in irrigation canals and swampy areas, supports populations of snails that host the parasite that causes the disease); and
- river blindness.

Water for wealth

To some extent, clean water can be said to be the fuel that powers a nation's economic engine. Fish farming, agriculture, the construction industry and manufacturing industries are just a few of the sectors that rely on clean water to operate and ensure productivity. Every day, these and other sectors of the economy rely on clean water to grow and to process and deliver their products and services.

Box 2. Water for wealth

Recreation and tourism
Recreation and tourism bring jobs and profits. Beautiful beaches, white-water rivers and calm, cool lakes contribute to flourishing recreation and tourism industries in several countries. Water has a powerful attraction for people, which translates into jobs and profits for many economies.

Real estate values soar at the water's edge
When it comes to real estate, a waterfront view is a prime selling feature—as long as the water is clean. Ocean, lake and riverfront properties often sell or rent at several times the rate of similar properties located inland. Community and business leaders also understand the potential value of waterfront locations. Today, waterfronts are often a focal point for urban renewal. With the emergence of riverfront parks, land near rivers is becoming highly desirable.

Water fuels manufacturing industries
The size and nature of industries vary widely, and yet nearly all of them share a common need—a reliable source of water to operate. In many cases, water is needed for production industries, such as:

- the fruit and vegetable processing industry—including fresh-pack and processing sectors;
- the meat and poultry processing industry—water for chilling, scalding, washing, cleaning and conveying waste;
- the food and beverage industry—water plays a large role in transporting, cleaning, processing and sanitation;
- textile industries—water is used extensively in processing; and bottling plants.

Box 3. Types of water—some common definitions

Artesian water/artesian well water
Water from a so-called 'confined' aquifer.

Drinking water
Water for human consumption.

Mineral water
Water containing not less than 250 parts per million total dissolved solids—mineral and trace elements—at source.

Purified water
Water that has been distilled, deionized, or produced by reverse osmosis or another process, and that meets the international standards for purified water.

Sparkling water
Water that contains carbon dioxide. (Note: soda water, seltzer water and tonic water are not considered sparkling waters. They are regulated separately, may contain sugar and calories, and are considered to be soft drinks.)

Spring water
Water that flows naturally to the surface from an underground formation.

Well water
Water from a hole bored, drilled or otherwise constructed in the ground, which taps water from an aquifer.

Water for food

Water as food

Food sufficiency is linked to the broader notion of nutrition sufficiency. Nutritional sufficiency presumes access to food coupled with a balanced 'food basket' and the capacity to absorb the nutritional value of the food consumed. Safe household water and sanitation are essential to nutritional sufficiency. As well as causing millions of premature deaths, unhealthy or inadequate diets contribute to high levels of sickness and malnutrition. Malnourished or sick people cannot be productive, hard-working, or innovative farmers or fishers. Much has been said about the importance of water to life—it has even been said that water is life itself. Water is essential for digestion. It is used to prepare juices, soft drinks and beverages. Water is also used to produce solutions of nutrients that are used to feed sick people through intravenous systems, when they cannot eat food in solid form.

Water and food production

Crop production depends on soil, water and light. Water is considered a key factor in agricultural production. Agricultural production uses 63% of all groundwater withdrawals, mostly for irrigation (Fig. 3).

Freshwater will be the key limiting factor in future food production and livelihood improvement. Around four tonnes of water (4,000 litres) are needed per person per day to produce the variety and quantity of food needed for a healthy diet. If water use is to be sustainable in the future, then we need to make better use of the rainwater that infiltrates the soil, and we need to manage better the water-consuming vegetation systems that provide life support to humans and nature. Such agricultural and natural vegetation consumes around 7,000 km^3 of water per year. In short, 50 to 100 times more water per person is needed to produce a healthy and nutritious food basket than is needed for a person's household domestic consumption.

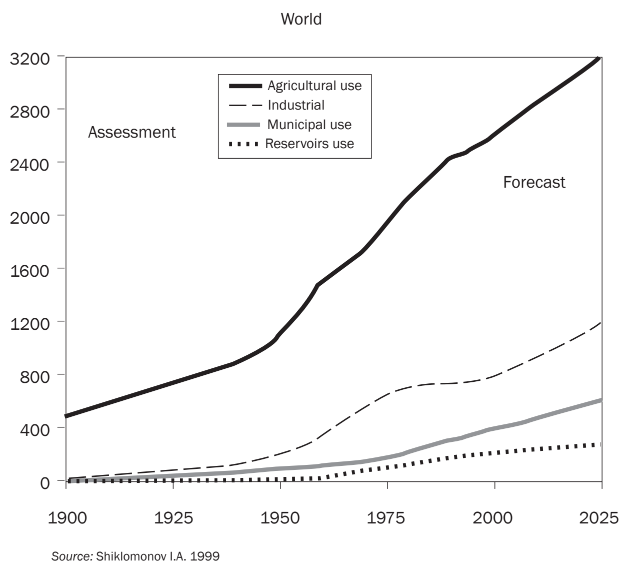
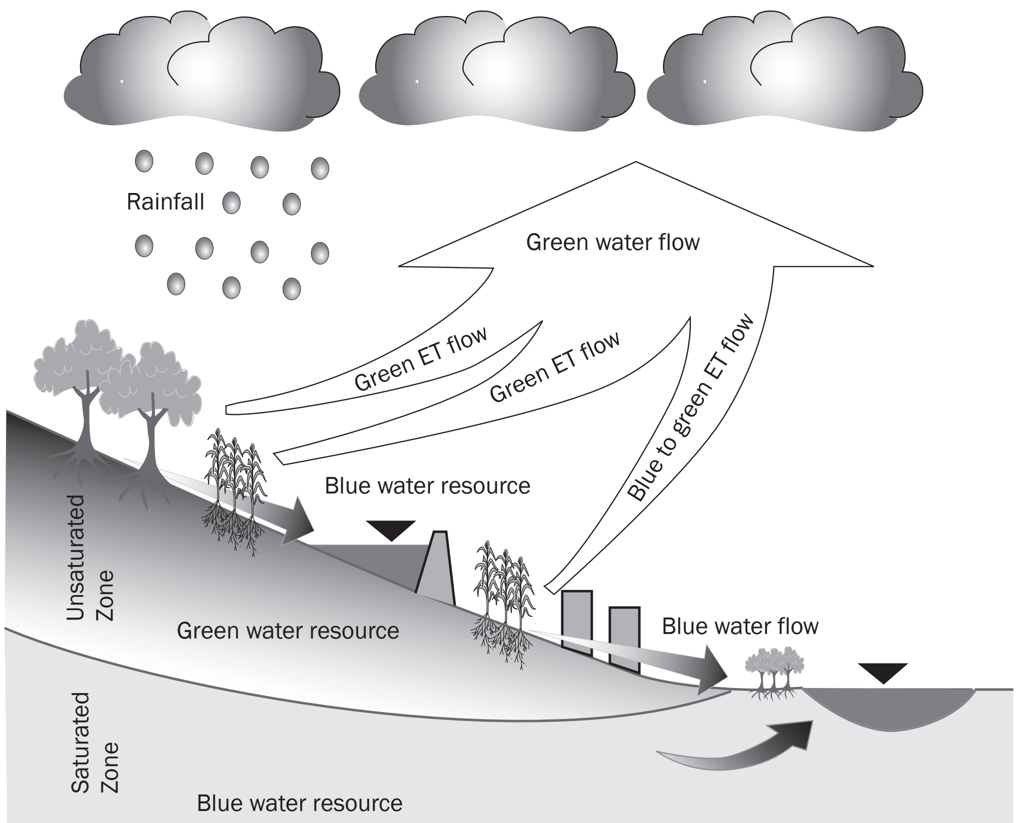


Figure 3: *Global water use 1900–2025: actual ('Assessment') and projected ('Forecast')*

1.4 Green water resources for sustainable production

The production of biomass for direct human use—food and timber—consumes by far the largest proportion of global freshwater resources (Fig. 3). Water is a critical element for plant biomass production.

During photosynthesis, plants take in carbon dioxide and transpire water vapour through their stomata. Evaporation from the soil, water bodies and plant foliage also produces water vapour. Because photosynthesis creates plant biomass, water vapour resulting from transpiration can be considered to be 'productive'. On the other hand, water vapour created by evaporation is a 'non-productive' loss of water to the atmosphere. Together, vapour fluxes as evaporation and transpiration are defined as *green water* flow. Rainfall that infiltrates into the soil, together with water in aquifers, lakes, and dams, is defined as *blue water* flow. Figure 4 shows the flow of *green water* resources in the atmosphere and in soil moisture in the unsaturated zone, and the flow of *blue water* in rivers and aquifers..



Source: Rockström J. 2003

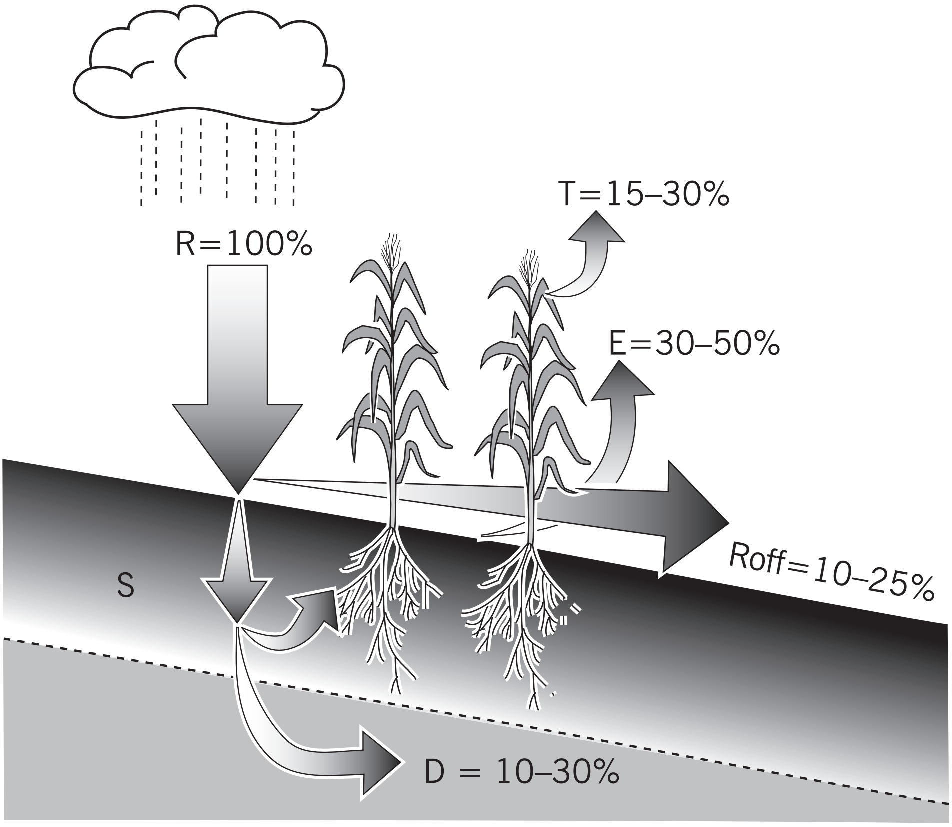
Figure 4: *Rainfall partitioning at the catchment scale—'blue' and 'green' water. ET=evapotranspiration.*

In other words, precipitation (*P*), is an undifferentiated form of fresh or ‘white water’ that is partitioned into either green flow or blue flow: green flow is vapour and blue flow is groundwater recharge and surface runoff. The proportion of green or blue flow deriving from *P* is determined at the land surface and in the unsaturated zone of the soil. Green water flow has two components: a *productive part* (transpiration **T**) that generates biomass in terrestrial ecosystems, and a *non-productive part* (evaporation **E**).

In the savanna zone, it takes around 2,000–3,000 m^3 or 300 mm/ha water to produce one tonne of grain. When compared with the average water consumption of 1,000–1,500 m^3/t globally, water productivity in savanna grain production is very low. The reason for this discrepancy cannot be explained by differences between temperate region crops, such as wheat and barley, and tropical crops, such as maize and sorghum. High rates of evaporation and evapotranspiration, coupled with low rainfall, lead to crop-water deficits and low biomass production.

This means that only a fraction of total rainfall is productive in tropical rainfed farming systems—the non-productive **E** flow greatly exceeds the productive **T** flow. Loss of productive water from on-farm water balances can be very high, particularly in the low-yielding farming systems that dominate this region, and where yields of staple grain are often only 1 t/ha. For tropical grains, such as maize, sorghum, and millet, only 10–30% of seasonal rainfall is productive green water flow, **T**, and up to 50% is lost as non-productive evaporation, **E**, either from the soil, or from plant canopies which have intercepted the rainwater.

A significant amount of precipitation leaves farms as blue water flow. Surface runoff accounts for up to 30% and often causes land degradation. Deep percolation accounts for another 25% (Fig. 5). Unless runoff evaporates during its journey downhill, it contributes to the blue water resource downstream, and so is not lost at the larger system scale. Likewise, in savanna zone, irrigated agriculture water-use efficiency tends to be only around 30%; the ratio of water consumed by irrigated crops to water withdrawn from the source is low.



Source: Rockström J. 2003

Figure 5: *Rainfall partitioning at the crop scale*

Water loss tends to be highest in the semiarid and dry subhumid zones—savanna agroecosystems—where most of the world's poorest countries are located. These hot spots of poverty and hunger also correspond to the regions facing the greatest freshwater deficits because of low rainfall coupled with extreme spatial and temporal variability. However, there are opportunities to tap the potential of currently ineffectively used on-farm water resources. This requires innovative strategies to manage sudden excesses of water and frequent periods of deficit—dry spells or drought.

Improving yields in rainfed agriculture requires minimizing water losses and improving productive water use. This means making productive use of precipitation that infiltrates the soil to boost biomass production. Integrated soil and water management—specifically soil fertility management, soil tillage to improve rainfall infiltration, and water harvesting—can significantly improve yields and water productivity (**WP,** m^3/t).

Rockström (2003) showed that the relationship between higher yields and water productivity is very dynamic, particularly where yields are low (1–3 t/ha), and where higher yields result in large improvements in **WP**. Rockström (2000) highlighted the major hydro-climatic hazards that affect yields:

- poor rainfall partitioning, where only a small fraction of rainfall reaches the root zone, coupled with crop competition for soil water;
- a high risk of periods of below-optimum cumulative soil-water availability during the growth season (i.e. not necessarily dry spells but periods when soil-water availability is below crop water requirements for optimal yields due to low cumulative rainfall); and
- a high risk of intermittent droughts or dry spells during critical crop growth stages (i.e. not necessarily a lack of cumulative soil-water availability but periodic water stress due to poor rainfall distribution).

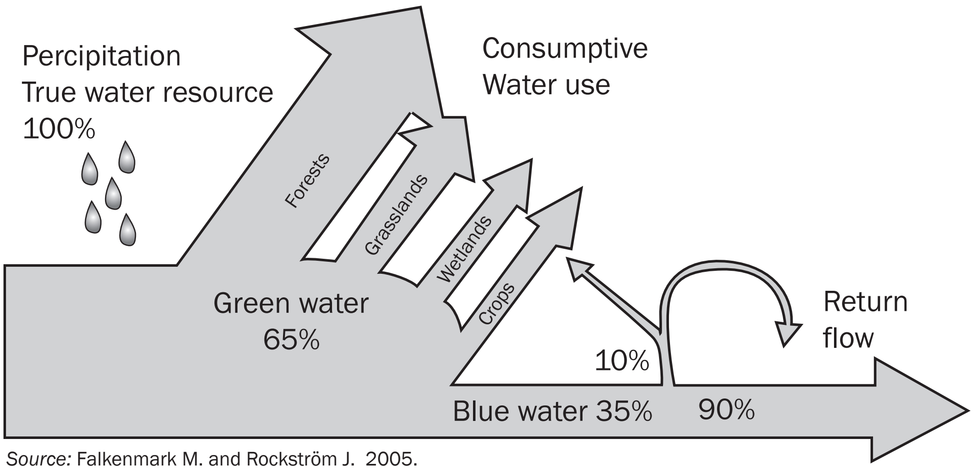
Using field data and water-balance models, Rockström *et al.* (1998) found that only 4–9% of seasonal rainfall (490–600 mm) returned to the atmosphere as transpiration. The cumulative 'loss' from soil evaporation and deep percolation amounted to 400–500 mm over three years (1994–96). This amount of water would be sufficient to produce 4 to 5 reasonable crops (assuming approximately 100 mm **T** for a grain yield of 700–1,000 kg/ha).

Rockström *et al.* (1998) indicated that rainfed crop yields can be doubled through innovations in soil, crop and water management. They estimated that integrated soil-water management can improve water productivity in the semiarid and dry subhumid savanna zones to around 1,500 m^3/t. Integrated soil-water management reduces non-productive evaporation and boosts productive transpiration, shifting a larger proportion of the on-farm water balance to transpiration (**T**).

1.5 Challenges and opportunities

According to the World Water Development Report (cited by World Bank, 2003), about 25,000 people die every day from hunger, while another 815 million suffer from malnutrition. Ensuring adequate water to both sustain human well-being and the ecosystems on which they depend, including agroecosystems, is imperative. On-farm rainwater harvesting—utilizing runoff that might otherwise be lost from the on-farm water balance—provides a promising mechanism to boost food production and overcome hunger and malnutrition.

On a global scale, two-thirds of continental precipitation, on average 110,000 km^3 annually, ends up as green water (Fig. 6). Around one-third flows into aquifers, rivers and lakes (blue water); of this, only about 12,000 km^3 is considered readily available for human use. Around 10% of blue water is withdrawn for municipal, industrial and agricultural use, less than 4% of the total water input. Green water—two-thirds of the water input—is retained as soil moisture, or returns to the atmosphere as evaporation or transpiration (consumptive water use). Two-thirds of the water input (precipitation) is therefore available for plant production. Forests consume most green water and only 6% is consumed in crop production. Of the 6% of green water used in crop production, two-thirds come from rain and one-third comes from irrigation using blue water. This means that crop production is mainly rainfed. Green water, therefore, is much more significant (volume-wise) in crop production than blue water.



Source: Falkenmark M. and Rockström J. 2005.

Figure 6: *Global water use—'blue' and 'green' water*

However, rainwater harvesting needs to be undertaken in such a way as to preserve the hydrological balance and biological functions of ecosystems. This is critical in marginal lands. Consequently, human activity to develop water resources must take into account the capacity of ecosystems to replenish and sustain themselves. The application and improvement of traditional and innovative technologies should therefore include measures to ensure sustainability and to safeguard water resources against pollution.

Agriculture is the largest consumer of freshwater (Fig. 3). Worldwide, agriculture uses around 70% of all fresh water withdrawals. In developing countries, rainfed agriculture on 80% of the arable land accounts for 60% of food production. The remaining 20% of arable land is irrigated, and produces 40% of all crops and close to 60% of all cereals. Recent estimates forecast that, by 2030, 45 million hectares will be irrigated in the 93 developing countries where populations will grow the most. About 60% of all land that could be irrigated will then be in use, but expanding the irrigated area will require 14% more irrigation water than at present. The challenge will be to use land and water more efficiently. Reports indicate that irrigation is extremely inefficient and that nearly 60% of irrigation water is wasted. Major issues of concern are the lack of irrigation technologies appropriate for small-scale farmers in developing countries, and the need to maximize use of water resources. Increasing the productivity of green water per unit of land is likely to be the best solution for increasing food production in these regions in the future.

As pressures to develop land for agriculture rise, more and more marginal areas in the world are being cropped. Many of these areas lie in the arid or semiarid zones, where rainfall is irregular and much of the precious precipitation quickly runs off the surface and is lost. Recent droughts have drawn attention to the risks to human beings and livestock that occur when rains falter or fail. While irrigation may be the most obvious response to drought, it has proved costly and benefits only a fortunate few. For this reason, interest is now increasing in the low-cost alternative to irrigation generally referred to as 'water harvesting'.

Projected water demand to 2050 will vary considerably by economic sector (Fig. 3) and by country. Water withdrawal in countries that have adequate water resources could grow by 100-200%. Table 2 shows estimates of the annual renewable freshwater, and per capita water availability for each of the SearNet countries for 1990, 2025 and 2050. Three of the 10 SearNet countries are currently water-scarce. In these countries, water from surface-water sources to expand irrigated agriculture will be limited. Some countries in this region experience wet seasons and here the focus should be on harvesting rainwater to augment water supplies in the dry season to increase food production.

In Sub-Saharan Africa, the amount of water retained in soils that can be used by crops is insufficient. Farming in the region suffers from poor management of rainwater—a no-cost water resource. The key to upgrading smallholder farming systems in dry sub-humid and semiarid Sub-Saharan Africa is harvesting and storing rainwater. For example, current crop yields in Kenya are 1 t/ha, 3–5 times lower than yields obtained by commercial farmers and researchers in similar agro-hydrological conditions. These low yields are attributed to poor crop-water availability due to variable rainfall, losses in on-farm water balance and poor crop management. Meeting the increase in demand for food, while using less water and land, requires farming systems and technologies that give greater yields per unit of water and land.

Over a 20-year period in semiarid East Africa, dry spells that limited crop yields occurred in at least 75% of growing seasons. Dry spells affect crops cultivated on soil with low water-holding capacity more seriously than crops cultivated on soils with a high water-holding capacity. Large on-farm water losses, due to deep percolation and runoff during rainy seasons, cause seasonal crop-water deficits. When rainwater is harvested and stored for supplemental irrigation, yields are 40% higher than conventional in situ water harvesting (Barron, 2004).

Farming is a risky business in climates where evaporation is high and rainfall is highly variable both spatially and temporally. Farmers are more willing and able to invest in fertilizers and other crop-management strategies if risks of crop failure due to crop-water deficits can be minimized. Good rainwater management strategies that encourage farmers to invest in productive cropping systems are a sustainable approach to realizing the UN Millennium Development Goals that aim to halve the number of poor and food-insecure people by 2015.

The impact of meteorological droughts on rainfed agriculture is complete crop failure. In semiarid regions, statistics indicate that meteorological droughts occur on average every 10 years (Stewart, 1988). However, research in several semiarid tropical regions shows that the occurrence of dry spells—short 2–4 week periods with no rainfall—far exceeds that of droughts (Stewart, 1988). Research in East Africa indicated that dry spells causing severe yield reductions occur once or twice in a 5-year period. Sivakumar (1992) showed that the frequency of seasonal dry spells lasting 10–15 days was independent of long-term seasonal average rainfall, which ranges from 200–1,200 mm in West Africa. Barron (2004), studying the frequency of dry spells in semiarid areas in Kenya and Tanzania, showed that the minimum probability (based on statistical rainfall analysis) of a dry spell lasting more than 10 days at any time during the growing season of a crop was 0.2–0.3, and that the probability of such a dry spell occurring during the sensitive flowering stage (maize) was 0.7. The implications of this research for agricultural production call for effective measures to mitigate the effect of dry spells at the farm level.

The economies of Sub-Saharan Africa countries largely depend on exploitation of natural resources, which are sensitive to climatic variability and climate change. These countries are likely to suffer disproportionately from climate change although their contribution to global warming, in terms of fossil fuel consumption, is limited.

Of the one billion poor people in the world today, 75% make their living in rural areas and depend on farming smallholdings for their livelihood. Improving agricultural productivity is still the key to rural development in poverty-stricken regions (World Bank, 2003). Unlocking the potential of rainfed farming systems in regions subject to frequent dry spells and droughts should therefore be a high priority in the achievement of the Millennium Development Goals. This will require innovative and viable options at the farm scale which do not compromise land and water resources for other users and the environment.

More than 600 million people, or 14% of the world's population, live in arid regions where the average annual rainfall is less than 300 mm. Here, the climate is too dry for successful cultivation of crops and water is scarce. An estimated 40% of the population of savannas live in tropical savanna agroecosystems. Approximately 60% (excluding the hyper-arid climate zones) of the African continent is classified as sub-humid or drier (UNEP, 1992; UNDP/UNSO, 1999). Food production in these zones is insufficient to meet current and future food requirements and to ensure a decent income for the millions of producers. Low on-farm crop yields of 1–2 t/ha or less reflect the low productivity of both land and water, and do not generate enough income to satisfy farmers' basic needs. Water is now the number one factor limiting food production in many parts of Sub-Saharan Africa.

1.6 Potential and prospects for green water

Since the total seasonal rainfall is often adequate for rainfed crop production, short—albeit critical—periods of water deficiency pose the greatest risk. Low crop yields not only result in minimal food production and income (and thus poor livelihoods for farmers), but also imply that large amounts of water that could be productive are lost. Water productivities of 5,000 m^3/t grain are common in rainfed systems in semiarid regions, such as Sub-Saharan Africa. Supplemental irrigation of about 100 mm per year, that is around 15% of total rainfall, can potentially double yields from, say, 1 to 2 t/ha. This means that water productivity would increase to 2,000 m^3/t. Globally, supplemental irrigation could reduce the need to withdraw an additional 1,500 km^3 of blue water per year for food production by 2050.

Harvesting rainwater for supplemental irrigation is common practice in India and China, and was a survival strategy in the Middle East and North Africa in ancient times, but is less practiced in Sub-Saharan Africa. Implementing rainwater harvesting for supplemental irrigation may create synergies with other extension and investment programs. When farmers realize the benefits of supplemental irrigation for mitigating dry spells they may be motivated to invest in fertilizers, improved seeds and pest management. Traditionally, various methods of rainwater harvesting (RWH) have been used over the centuries. Early agriculture in the Middle East was based on techniques such as diverting '*wadi*' flow (spate flow in normally dry water courses) onto fields. Rainwater harvesting was also practiced in the Negev Desert, the deserts of Arizona and northwest Mexico and southern Tunisia (Pacey and Cullis, 1986). The importance of traditional, small-scale rainwater harvesting systems in Sub-Saharan Africa has also recently been recognized; these include simple lines of stone to prevent runoff in Burkina Faso and Mali, and earth-bunding systems in eastern Sudan, Kenya and the rangelands of Somalia, for example.

Agriculture in Sub-Saharan Africa is mainly rainfed; few water storage and irrigation systems exist. There is a need to broaden the global water debate beyond the current focus on managing blue water resources in rivers, lakes and aquifers, providing potable water, financing water supplies and using irrigation to produce food. For water use to be sustainable, then better use should be made of (1) the rainwater that infiltrates the soil, and (2) the water taken up by the vegetation that provides life support to humans and nature. The need for a broadened approach to water will become more critical as populations continue to grow and rural–urban migration accelerates in this water-scarce region.

The core issue should therefore be to improve green water productivity, both directly, for food production, and also indirectly, to support ecosystem services. Water productivity (the produce or value derived, or potentially derived, from each unit of water that is put to beneficial use) in crop production must be improved to produce more crops with less water. Evaporation needs to be reduced and transpiration needs to be increased to improve water productivity. Crop and land management methods that convert non-beneficial evaporation to beneficial transpiration, together with tillage and water management techniques that increase the proportion of rain which infiltrates the surface and forms vital soil moisture, can improve yields. Developing more drought- and salt-tolerant plant varieties can also increase crops' water productivity.

A change in focus from downstream blue water resources to upstream green water resources provides opportunities to produce more food per drop of water. Such a shift towards rainwater management forms a rational entry point for integrated agricultural water management that encompasses both green rainfed withdrawals and blue irrigation withdrawals. Moreover, the shift towards an upstream focus also opens up possibilities to take advantage of gravity flow in water management, with particular benefits for resource-poor smallholder farmers.

Most future population growth will be in developing countries, where currently one billion people are malnourished. Of the world's poor, 70% live in rural areas and depend on rainfall-based sources of income (rainfed agriculture). In Sub-Saharan Africa, over 60% of the population depends on rain-based rural economies. These economies generate between 30–40% of gross domestic product (World Bank, 2003). Globally, 80% of agriculture is rainfed (the remaining 20% is irrigated) and pressure is growing to increase agricultural productivity by raising yields per unit of soil and water.

Rainfall is a renewable water resource with a cycle of 8 hours to one year (Table 1). Renewable global water resources are estimated to be 42,750 km^3/yr, and are very variable in space and time. Previous approaches to improving food production have focused solely on irrigation. Today, 60–70% of global food production, and over 60% of food in 80% of developing countries, is produced from rainfed agriculture. Most agriculture in Sub-Saharan Africa is rainfed (over 95% of the agricultural land) because Africa lacks the enormous amounts of water that, for example, flow from the Himalayas to South Asia. Future food production thus cannot be addressed unless rainfed production is incorporated, and incorporated more effectively.

It has been acknowledged that groundwater storage capacity in many dryland areas is inadequate to meet people's needs; hence, other methods of water harvesting and storage need to be explored. There is a need to document, strengthen and popularize traditional water-harvesting and storage systems to ensure that available precipitation is effectively used. Groundwater resources will become increasingly important in dry areas, especially those far from rivers and other surface water.

In the last two decades, interest in rainwater harvesting has grown. In rural areas, rainwater harvesting is now an option, along with more 'traditional' water supply technologies. The technology is particularly important and relevant for arid and semiarid lands, small coral and volcanic islands, and remote and scattered human settlements. A number of external factors have stimulated interest, including:

- the shift towards community-based approaches and technologies that emphasize participation, ownership and sustainability;
- the increase in small-scale water supply technologies for productive and economic purposes (livelihoods approach);
- the decrease in the quality and quantity of groundwater and surface water;
- the failure of many piped water supply systems due to poor operations and maintenance;
- the flexibility and adaptability of rainwater harvesting technology;
- the replacement of traditional roofing (thatch) with impervious materials (e.g. tiles and corrugated iron); and
- the increased availability of low-cost tanks (e.g. made of ferro-cement or plastics).

The potential of water harvesting for improved crop production received great attention in the 1970s and 1980s. At that time, widespread droughts in Africa left a trail of crop failures and seriously threatened the lives of humans and livestock. Consequently, a number of water harvesting projects were set up in Sub-Saharan Africa with the objectives of combating drought by improving crop production and, in some areas, rehabilitating abandoned and degraded land. However, few projects succeeded in combining technical efficiency with low costs, and few new technologies were accepted by local farmers and agro-pastoralists. Failure was partly due to the lack of technical 'know how' but also to approaches inappropriate to the prevailing socioeconomic conditions.

More recently, traditional water management techniques have attracted new interest. These old techniques are easy to implement, require only small capital investments and are becoming popular.

As traditional water-management techniques vary according to the amount of rainfall, its distribution, topography, soil type, soil depth and local socioeconomic factors, they tend to be very site-specific. Local conditions strongly influence water harvesting methods and lead to widely differing practices, for example bunding, pitting, micro-catchment water harvesting, and flood water and groundwater harvesting (Critchley and Siegert, 1991).

This book is therefore written for practitioners and stakeholders in the SearNet region. The aim is to provide a resource and technical know how on rainwater harvesting. The book is the final output of a regional effort undertaken to:

- document examples, information and experiences on managing rainwater harvesting in eastern and southern Africa;
- share lessons from these experiences with relevant practitioners in the region with

a view to upscaling and upgrading successful rainwater management systems and projects;
- provide a reference on rainwater harvesting for governments, learning institutions and development agencies to use when developing policies, curricula and project plans; and
- provide a reference and guide for rainwater management implementation, monitoring and evaluation.

Because rainfed agriculture will continue to play the major role in producing more food to support growing populations in developing countries, the focus should be on rainwater harvesting at the small catchment or watershed scale: the most relevant scale for farmers. The systems and technological options described in this book are mainly for rainwater management at this scale.

This handbook first gives an overview of the climate of Africa to provide the context for effective green water management. The following chapters then document issues, approaches and technologies for adapting or adopting rainwater management systems: technical and technological options; crop production; livestock production; ecosystem and ecological sustainability; economics of rainwater management; extension and training; gender, socio-cultural and political considerations; sustainability; policy and legislation; and monitoring and evaluation.

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Chapter 2

The Climate of Africa

2.1 Characteristics

The climate of Africa is influenced by large-scale (synoptic) and small-scale (meso-scale) systems. The main synoptic systems are the Intertropical Convergence Zone (ITCZ), extra-tropical weather systems (sub-tropical high pressure systems), squall lines, easterly/westerly wave perturbations, jet streams and tropical cyclones (Goddard and Graham, 1999; Nicholson and Selato, 2000). Other large-scale systems are monsoonal flows, teleconnections (global-scale climate anomalies associated with Sea Surface Temperatures), Indian Ocean Dipole patterns (Reason, 2001; Webster *et al.*, 1999), Quasi-Biennial Oscillation (QBO) in the equatorial lower stratospheric zonal wind (Reason *et al.,* 2000, Loschnigg, 2003), inter-seasonal, 30–60 day Madden Julian wave, and solar and lunar forcing (Ogallo 1988, 1989; Indeje and Semazzi, 2000; Anyamba, 1992; Mukabana and Pielke, 1996). These classical climate patterns are further modified in some areas by meso-scale features, such as mountains and large lakes, which create small-scale circulation patterns that interact with the large-scale flow. These factors bring about the four climatic zones in Africa, namely tropical rain forest, savanna, desert and Mediterranean zones (Fig. 7).

Tropical rain forests lie in the centre of the continent and on the eastern coast of Madagascar. Here, annual rainfall averages about 1,780 mm and temperatures average 26.7°C. To the north and south of the tropical rain forest is a savanna zone, which extends over about one-fifth of the continent (Fig. 7). Here, the climate is characterized by a wet season in the summer and a dry season in the winter. Total annual rainfall ranges from 550 mm to more than 1,550 mm. The savanna consists mainly of grassland with scattered trees. To the north and south of the equator, the savanna zone grades into arid or desert zones. Average annual rainfall ranges from 250–500 mm and is concentrated in one season. Africa has a proportionately larger area of arid and desert zones than any continent except Australia. The Sahara Desert in the north and the Kalahari and Namib Deserts in the southwest, have less than 250 mm of rainfall annually. In the Sahara, daily and seasonal extremes of temperatures are large. The average temperature in July is more than 32.2°C; during the cold season, temperatures often drop below 0°C at night. Mediterranean zones are found in the extreme northwest and southwest of Africa. These regions are characterized by mild, wet winters and warm dry summers (Fig. 7).

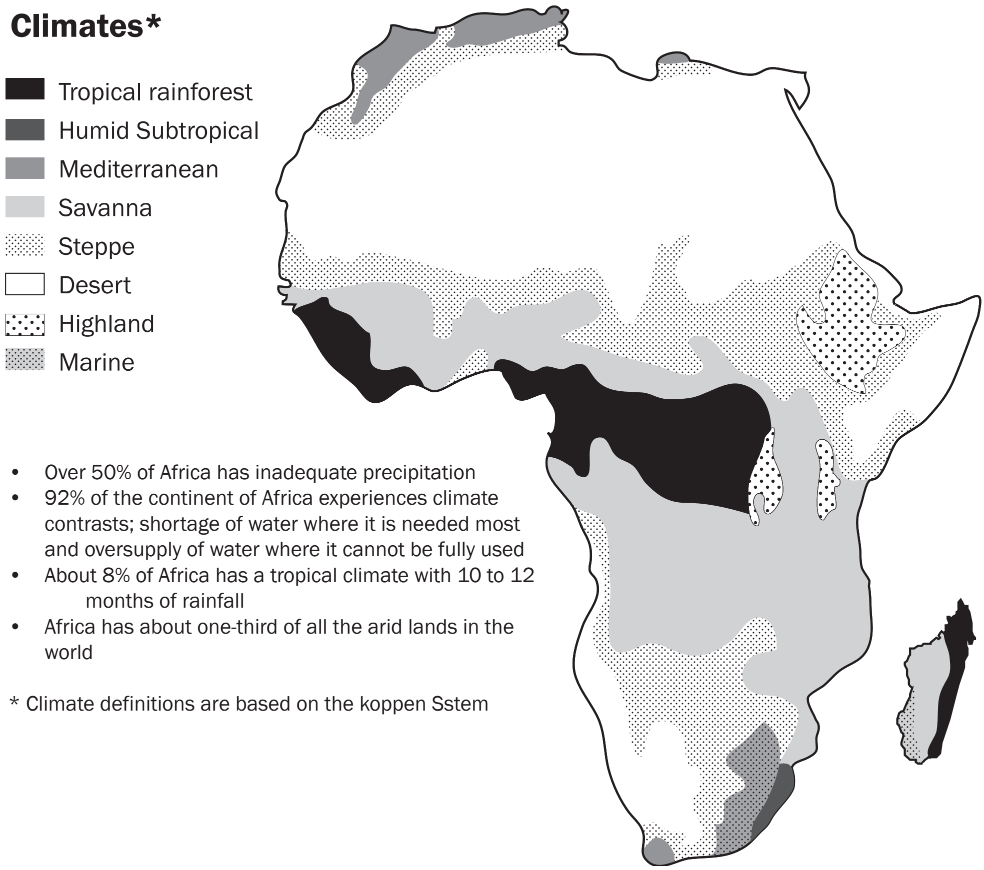


Figure 7: *Climatic zones of Africa*

2.2 Rainfall regimes

Rainfall regimes in Africa are complex. Mean annual rainfall varies from 0 mm in the desert regimes to as high as 5,000 mm in tropical rain forests (Fig. 8). Due to the nature of the rain-producing systems, rainfall is strongly seasonal. There are three major rainfall regimes: bimodal (two rainfall peaks), unimodal (one rainfall peak) and trimodal (three rainfall peaks). The first two regimes are mainly a result of the migration of the sun across the equator twice a year resulting in changes in the seasons, while the trimodal type results both from the sun's migration and the west–east fluctuations of the meridional (north–south) arm of the Intertropical Convergence Zone (ITCZ; Fig. 9) which causes moisture influx from the Congo forests and the Lake Victoria influence.

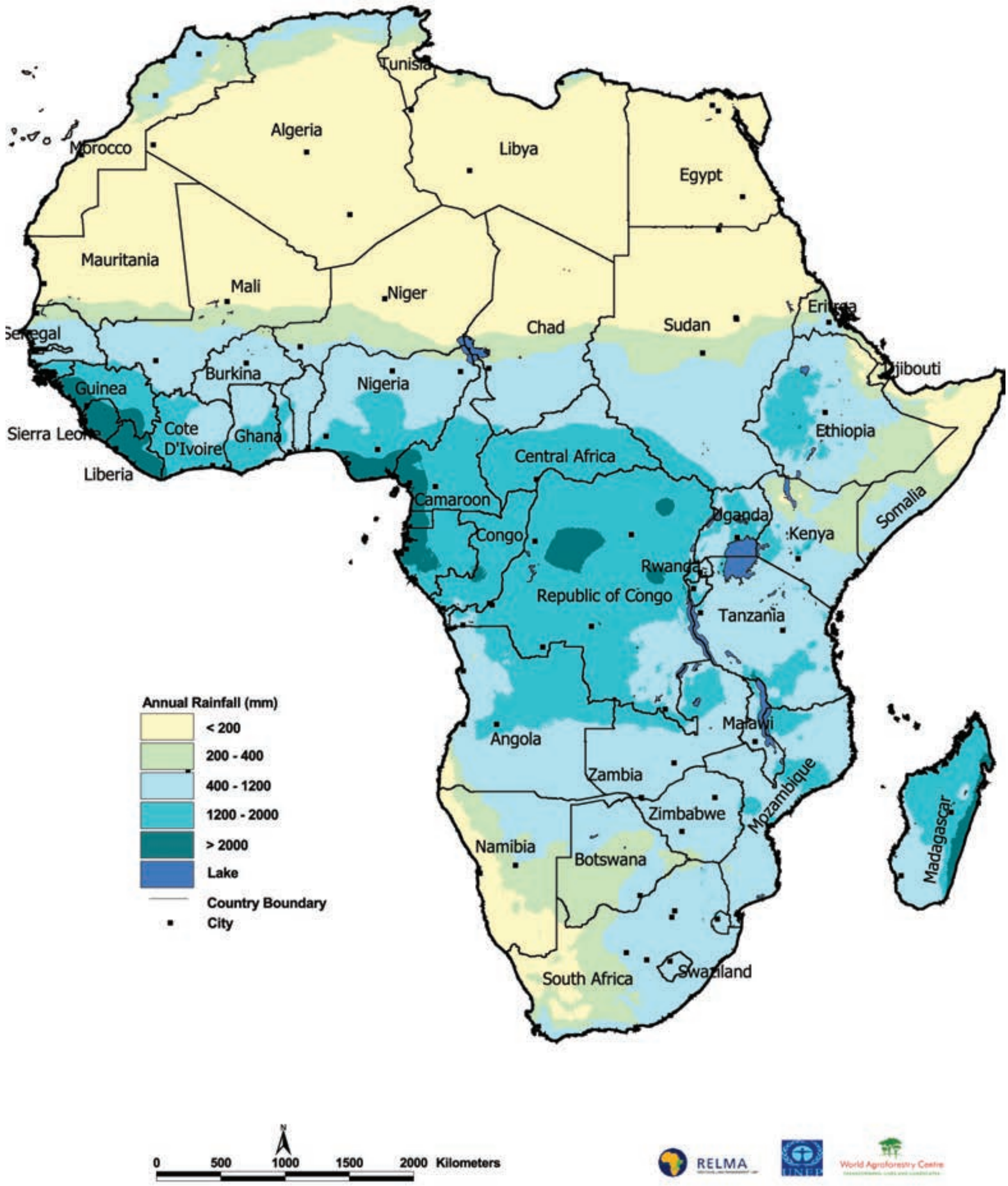


Figure 8: *Africa—map of annual rainfall*

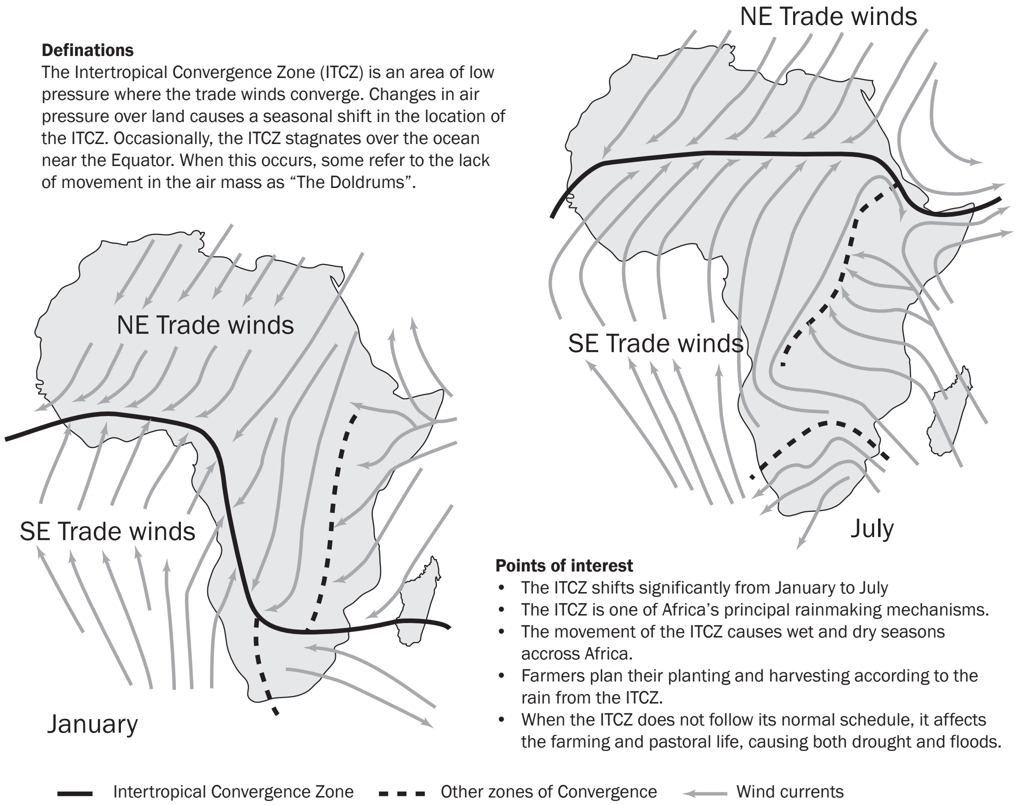


Figure 9: *The Intertropical Convergence Zone*

Tropical regions (10°N–10°S) experience bimodal moderate to heavy precipitation from March to May and September to November, when the sun crosses the equator and winds converge from north and south. Moderate to heavy precipitation is associated with the Intertropical Convergence Zone (ITCZ) or the Intertropical Discontinuity (ITD) as in the case of equatorial and tropical areas. The ITCZ moves in harmony with the movement of the overhead sun, concentrating peak summer rains in the northern and southern parts of Africa from June to August, and December to February, respectively (Fig. 9). When the sun migrates towards the poles, the ITCZ and its associated rain belt move with it. During the southern hemisphere winter (June–August), when the ITCZ is in the north (30°N–60°N), the rain belt shifts northwards and it rains in Ethiopia, Sudan, Eritrea, Somalia, Djibouti, Chad and West Africa. In the southern hemisphere summer (December–February), the reverse occurs as the sun is south of the equator and the ITCZ shifts south, resulting in heavy rainfall in countries to the south of the equator, such as Tanzania, Botswana, Zimbabwe, Zambia, Mozambique and Swaziland.

The north and south extremities of the continent experience rain mainly once during summer (unimodal). But, during winter, the passage of mid-latitude phenomena, such as frontal systems, embedded in the westerly wind regimes, may also be associated with rain. However, regions near large water bodies and within equatorial Africa either receive substantial rainfall throughout the year or receive a third peak of rainfall. These regions include central Africa, the southern coast of West Africa, and parts of Uganda and Kenya surrounding Lake Victoria. In central Africa, the trimodal regime is attributed to the influence of the Congo air mass over the Congo tropical forests, while western Kenya and Uganda are influenced by the Congo air mass and the large mass of water in Lake Victoria.

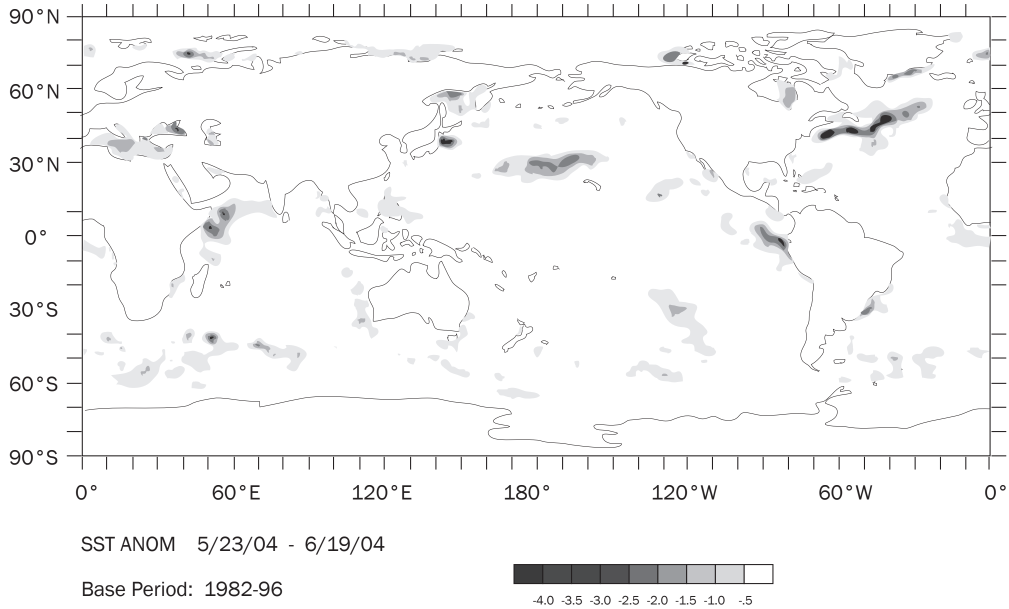
It is worth noting that many parts of the subtropics are characterized by dominant quasi-permanent high pressure descending air masses with very limited cloud and rainfall. Good examples of deserts in these climatic regimes are the Sahara Desert in the north and the Kalahari Desert in the south.

2.3 Factors that influence rainfall over Africa

Rainfall in Africa is determined by sea surface temperature (SST), atmospheric winds, fluctuations in subtropical high pressure systems (anticyclones) in the Indian and Atlantic Oceans, El Niño Southern Oscillations (ENSO), the Intertropical Convergence Zone (ITCZ), tropical cyclones and mountains, forests and lakes.

Sea surface temperature (SST)

Sea surface temperature influences the duration and amount of seasonal rainfall across continents. This is because ocean temperature affects pressure, wind and moisture patterns across the globe (Fig. 10). Rainfall and the sea surface temperature (SST) are strongly related. Consequently, SSTs can be used to predict weather patterns. For example, the Drought Monitoring Centre Nairobi (DMCN) uses SSTs to predict seasonal rainfall over the Greater Horn of Africa (GHA). Therefore, potential rainwater harvesting areas can be predicted well in advance (3 months). In addition to predicting rainfall, SSTs are also used to track ocean currents and monitor El Niño and La Niña events.



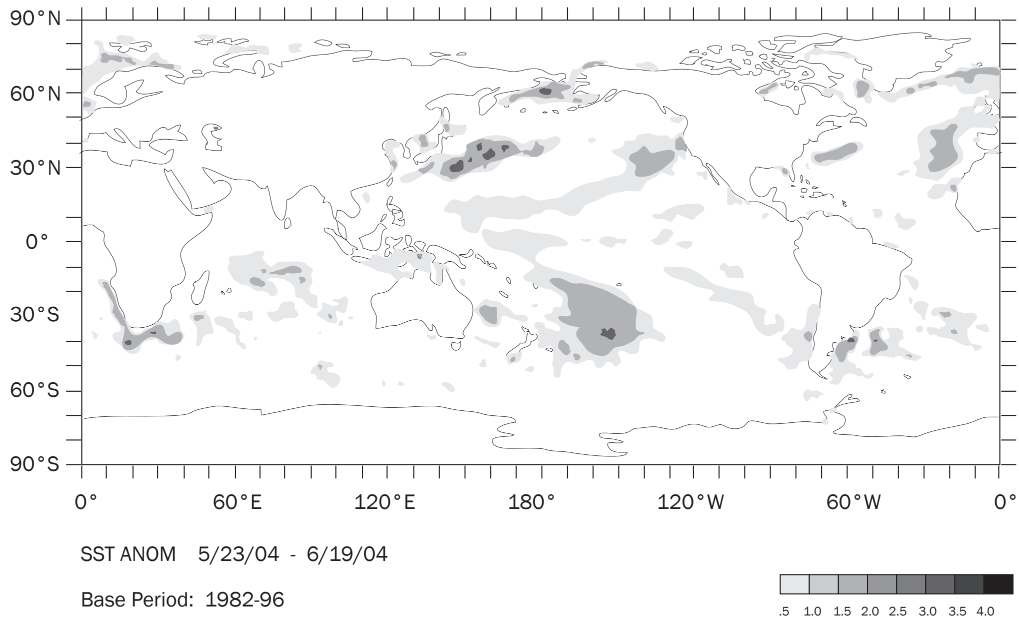


Figure 10: *Warm and cool sea surface regions*

Atmospheric winds

Winds are very important mechanisms for transporting moisture. Monsoon winds over Africa transport moisture from the extra-tropical regions to the tropics, where they deposit it as rain. Monsoons, or seasonal winds, generally blow from the northeast for one half of the year, and from the southwest for the other half. Torrential rainfall often accompanies these winds. Monsoons occur in the tropical regions of northern Australia, Africa, South America and the USA. However, monsoons are most important in south and southeast Asia, particularly in India.

During the southern hemisphere summer, high pressure develops over the Asian subcontinent, driving dry, northeasterly winds across eastern Africa and resulting in dry, sunny weather over northern and eastern Africa. But, cool, stable air masses from the south move across eastern Africa during the northern hemisphere summer, driven by southeasterly and westerly winds. However, from April to May and October to December, the monsoon winds converge over the equatorial regions resulting in heavy rain in the tropics. Monsoons are unreliable and the amount of rainfall varies considerably from year to year. Low rainfall negatively affects agriculture, and water supplies in general, but, on the other hand, even moderate rainfall can often cause floods.

The relationship between the stratospheric and tropospheric winds is very important for rainfall in the tropics. The fluctuating wind shear in the stratosphere (30–60 days), known as the Quasi-Biennial Oscillation (QBO), influences ozone levels, temperature and surface winds and tides; it also causes sudden warming, as well as hurricanes and changes in sea surface temperature (SST). The easterly and westerly phases of the QBO affect zonal winds in the lower stratosphere while the monsoon is stronger during the westerly phase of the QBO than during the easterly phase. Study results support the hypothesis that changes in the lower stratospheric vertical circulation affect the height of the tropopause and, hence, the depth of convection which leads to heavy convective rainfall. The westerly phase of the QBO over Nairobi results in heavy rainfall over western and central Kenya. Therefore, the strength and persistence of monsoonal and stratosphere winds are good indications of the amount of rainfall that can be expected and, in turn, the amount that can be harvested.

Subtropical high-pressure systems (anticyclones)

An anticyclone is an area of high pressure caused by a large mass of descending air. These descending air masses can be up to 12 km deep and are very stable. Differences in pressure between high- and low-pressure air masses create winds that flow from high-pressure areas to low-pressure areas.

Anticyclones form mainly outside the tropics, in mid-latitudes. The mid-latitudes are sometimes referred to as the ‘hose’ latitudes, since they pump in moist air masses to the tropics. Semi-permanent anticyclones over the southern Atlantic and southwest Indian oceans draw up moisture, which eventually falls as rain in Africa. However, the anticyclone over the Asian sub-continent drives dry northeasterly monsoon winds during the southern hemisphere summer and causes dry, hot weather in northeast Africa. Thus, in countries to the south of the equator, it would be advisable to harvest rainfall during the southern hemisphere summer, whereas in countries to the north of the equator it would be best to harvest rainwater during the northern hemisphere summer.

El Niño Southern Oscillation (ENSO)

Definition of El Niño and La Niña

The term El Niño (Spanish for 'the Christ-child'), refers to the periodic build-up of unusually warm water in the eastern central equatorial Pacific Ocean (Fig. 11). On the other hand, La Niña refers to unusually cold water in the same ocean basin. The warming and cooling of the eastern equatorial Pacific Ocean region (El Niño and La Niña events) influence the atmosphere and neighbouring oceans in various ways.

Warming and cooling are associated with changes in atmospheric pressure known as the Southern Oscillation (SO). The Southern Oscillation is a 'seesaw' in atmospheric pressure between the western and eastern equatorial Pacific Ocean. The centres of activity are in Indonesia (represented by Darwin) and the central Pacific (represented by Tahiti). The Southern Oscillation Index (SOI) is the difference in standardized pressure between the two centres. Since the SO is closely linked to El Niño episodes, they are collectively referred to as El Niño/Southern Oscillation (ENSO) (WMO, 1984), and El Niño and La Niña phenomena are simply referred to as the warm and cold ENSO phases, respectively. The warm and cold phases of El Niño/La Niña events are known to trigger worldwide anomalies in sea surface temperatures (SST) and the circulation of the ocean currents (Fig. 11). ENSO events recur every 2–7 years and usually last from 3–6 months, although sometimes they can persist for up to 24 months. El Niño events are sometimes immediately followed by La Niña episodes. However, the evolution and impacts of the events are not identical. They merely signal a major departure from normal climatic conditions.

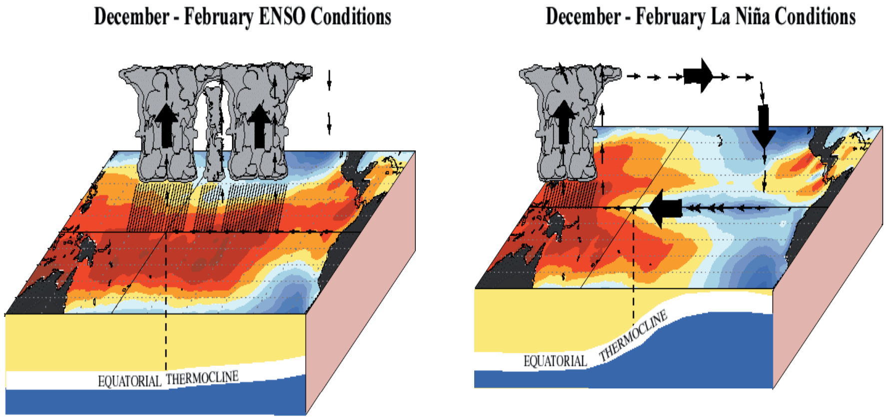


Figure 11: *Wind circulation during El Niño and La Niña*

Worldwide effects of ENSO

ENSO events are known to have severe global climatic implications, especially in the tropics. During a strong El Niño event, anomalous heavy convective rainfall occurs over the central eastern Pacific, central western equatorial Indian Ocean, along the coast of eastern Africa and the Atlantic equatorial coast of Africa, in northwest South America, and in the northern parts of the Greater Horn of Africa (GHA). The observed impacts are very variable, both in time and space (Ogallo, 1988). In southern Africa, warm (El Niño) ENSO episodes tend to be associated with rainfall deficits, whereas in eastern Africa, they are associated with above-normal rainfall. The situation is reversed during cold (La Niña) ENSO episodes. The 1997–98 El Niño event is considered to be the strongest in the twentieth century, comparable to and even surpassing even the famous 1982–83 event (Obasi, 1999). In most cases, El Niño episodes are followed by La Niña episodes and give a good indication of rainwater harvesting opportunities.

Overview of ENSO influence on the climate of Africa

Extreme climate events, such as droughts and floods, are very common in some regions of Africa. Although ENSO impacts are strongest in the Pacific region, records show that severe droughts and floods in Africa are also associated with ENSO events. Recent studies showed that, although ENSO signals are discernible, both the Atlantic and Indian Oceans play significant roles in determining climate in the Sahel, eastern and southern Africa sub-regions. In addition, large inland lakes, and complex inland topography, including the Great Rift Valley, also play significant roles in modulating regional climate anomalies.

ENSO is the dominant factor in inter-annual climate variability over eastern and southern Africa (Nicholson and Entekhabi, 1986). The effects of ENSO, however, vary spatially and temporally. However, rainfall depends not only on the ENSO phase (onset, peak and withdrawal) but also on sea surface temperature in the Atlantic and Indian Oceans.

Eastern and southern Africa

Recent studies showed that ENSO events correlate strongly with seasonal rainfall anomalies in the region. The correlation varies significantly from season to season and also with specific ENSO phases. In general, above/below average rainfall conditions are common from March to May and October to December during the onset of the warm/cold ENSO events. On the other hand, below/above average rainfall conditions dominate many areas of the sector in June–September at the onset of the warm/cold ENSO event. In eastern Africa, the warm ENSO phase results in above average rainfall, whereas in southern Africa it is negatively correlated with these events (Nicholson and Kim, 1997) from October–December.

The east Africa sub-region can be divided into three sectors based on the rainfall regimes. The northern sector receives peak rainfall during the northern hemisphere summer (June–September), the southern sector receives peak rainfall during the southern hemisphere summer (December–February), and the equatorial sector receives rainfall throughout the year.

Various studies have shown that the onset of warm/cold ENSO events is often associated with below/above average rainfall over most of the northern sector, as well as over southern parts of the eastern sector. Figure 14 (a and b) shows rainfall anomalies over the northern sector (Greater Horn of Africa) during warm and cold ENSO phases in summer while Figure 15 (a and b) shows rainfall anomalies over East Africa in November during an ENSO event. The blue and dark blue shading indicate areas where rainfall is abnormally high, and hatched shading indicates areas where rainfall is abnormally low (DMCH, DMCN and Majugu, 2002).

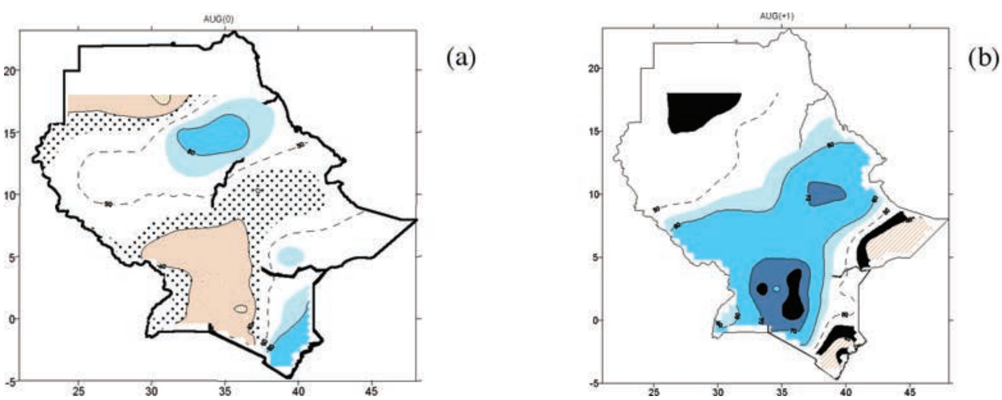


Figure 14: *Rainfall anomalies during (a) warm and (b) cold ENSO events*

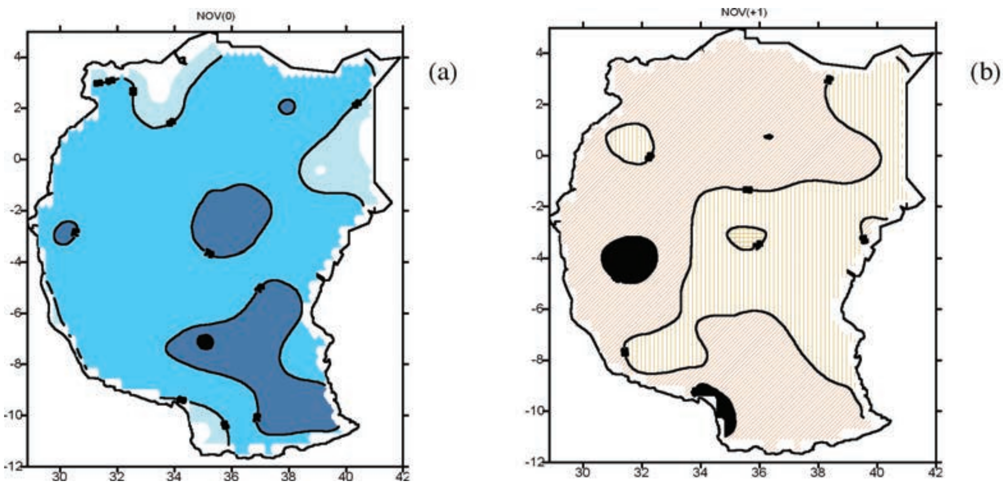


Figure 15: *Rainfall anomalies during warm ENSO (a) and cold ENSO (b) events*

In southern Africa, there is a strong correlation between the onset of warm ENSO phases and drought. During most warm ENSO episodes, southern Africa experiences considerable rainfall deficits (Fig. 16), whereas in cold ENSO phases, such as in 1999/2000, the sub-region receives high rainfall. Once again, this information can be very useful in planning rainwater harvesting.

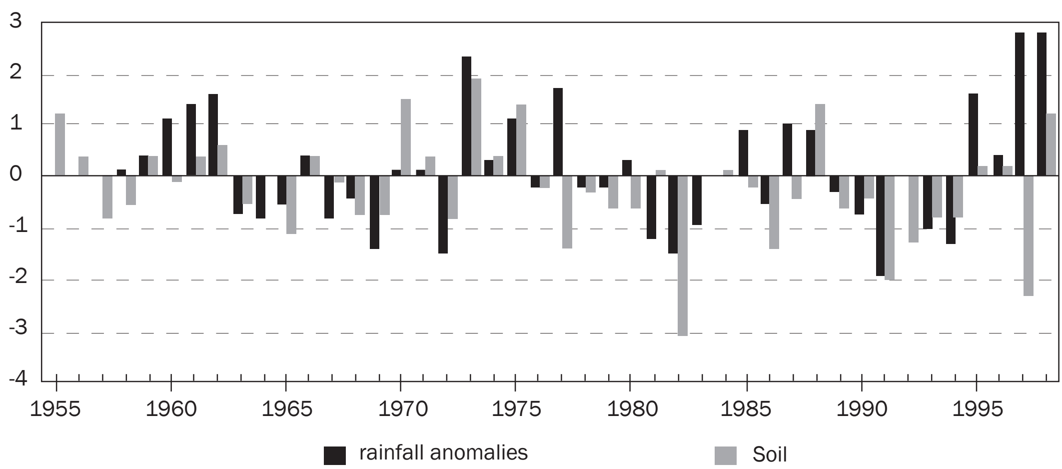


Figure 16: *Rainfall anomalies in Southern Africa during cold ENSO phases (Garanganga, 2003)*

Tropical cyclones

A tropical cyclone is a synoptic low-pressure system in tropical or sub-tropical latitudes characterized by convection (thunderstorms) and cyclonic surface wind circulation (Fig. 17).

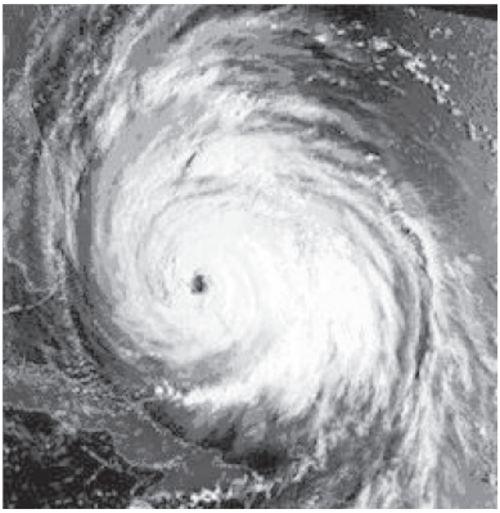


Figure 17: *Mature tropical cyclone*

The diameter of cyclones ranges from 200 to 2,000 km. Tropical cyclones have warm centres, very steep pressure gradients and strong cyclonic (clockwise in the southern hemisphere) surface winds. Tropical cyclones with wind speeds over 33 m/s (64 knots (kt), 74 mph), are known as 'hurricanes' (north Atlantic, northeast Pacific and south Pacific east of 160°E); a 'severe tropical cyclone' is known as a 'typhoon' (northwest Pacific, southwest Pacific west of 160°E and southeast Indian Ocean). Tropical cyclones with wind speeds of less than 17 m/s (34 kt, 39 mph) are known as 'tropical depressions'. When winds in tropical cyclones exceed wind speeds of 17 m/s they are known as 'tropical storms' and are assigned names. Factors that encourage tropical cyclones to form and persist include:

- Warm ocean water (at least 26.5°C) to generate heat and fuel the engine of a tropical cyclone.
- Potentially unstable atmosphere. Convection currents transmit the heat stored in the ocean into the atmosphere and initiate tropical cyclones.
- Relatively moist layers near the mid-troposphere (5 km). Dry layers at mid-level in the atmosphere do not encourage widespread thunderstorms.
- Heat rising from the ocean at least 500 km from the equator.
- Low-level inflow (convergence) and upper-level divergence to create near-surface disturbance.

Torrential rain always accompanies tropical cyclones—up to 3,000 mm in a single storm. Such heavy rain causes loss of life and floods and landslides, and destroys property. In Africa, the tropical cyclone season starts in November and lasts until April, with a peak frequency in January and February. The weather in South Africa is only affected by tropical cyclones moving into the Mozambique Channel. When this happens, cyclones suck moisture from surrounding areas and the interior remains dry. The best time for rainfall harvesting in South Africa and neighbouring countries is, therefore, between

November and February. During this period, it is dry in eastern Kenya, Somalia and parts of northern Tanzania, as cyclones suck up the moisture and carry it south and into Indian Ocean. But, when tropical cyclones move eastwards towards the east African coast, they boost convergence and produce heavy rain. Tracking the path of tropical cyclones helps effective rainwater harvesting.

The Intertropical Convergence Zone (ITCZ)

As mentioned earlier, a rain belt (the ITCZ) and the sun migrate twice a year across the equator. The ITCZ, a low-pressure zone characterized by converging winds from both the south and the north (Fig. 18), generates heavy convective rainfall over the zones of convergence. Therefore, the ITCZ is the most important factor determining when, and where, to harvest rainfall.

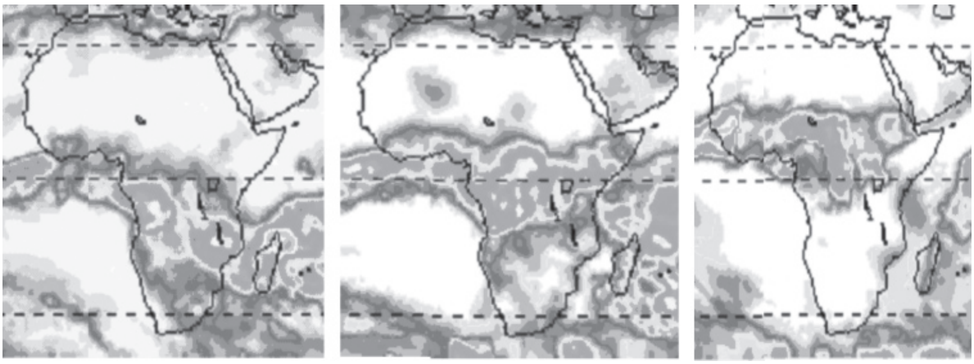


Figure 18: *Rain belt (a) during summer in the south, (b) during equinoxes, (c) during summer in the north*

The best time to harvest rainfall in the southern parts of the continent is during the southern hemisphere summer. However, in the north the best time is during the summer, while in the tropics the best times are from March to May, and October to December (Fig. 18 a–c).

Local influences

Rainfall in Africa is also influenced by local features, such as lakes, forests and mountains. Large water bodies (lakes), mountains and forests receive rainfall throughout the year. Coastal regions also receive substantial amounts of rainfall. Moisture from lakes and forests rises into the atmosphere, and wind patterns are affected by topography—resulting in prolonged rainy seasons. Complex mountain systems also create unique climatic zones, where rainfall is higher on the windward side. Mountainous areas, therefore, are promising areas for rainfall harvesting.

2.4 Vulnerability of Africa to variations in climate

Many socioeconomic activities in Africa depend heavily on weather/climate, and especially rainfall. The formal and informal economies of most African countries are strongly based on natural resources: agriculture, pastoralism, logging, ecotourism, and mining dominate. Consequently, climatic variations that affect these activities have a severe impact on the economic well-being of these states. On a global scale, it is estimated that about 75% of natural disasters are related to extreme weather and climate events, such as floods, droughts and heat waves. In Africa, because most people are poor, and African countries are the poorest and least-developed nations in the world, national economies are highly vulnerable to such events. When averaged across Africa, per capita gross domestic product (GDP), life expectancy, infant mortality and adult literacy are all in the bottom quartile globally, although individual nations may perform somewhat better on one or more of these indices.

Impacts of weather on socioeconomic activities

Extreme climate events, such as droughts and floods, have far-reaching socioeconomic impacts—loss of life and property, destruction of infrastructure and large losses to the economy. They also have harsh negative impacts on agriculture, livestock, wildlife, tourism, water resources and hydroelectric power generation, and on many other socioeconomic sectors. Many developing countries do not have the capacity to cope with the impacts of such events and often rely on support from the international community. Bad weather and extreme climate events also affect the welfare of communities and tend to deepen poverty, especially in regions where people rely on rainfed crops, livestock and hydroelectric power. The destruction of crops by floods, and low yields that result from drought, reduce the economic status of most rural communities; this especially affects women, who form the majority of the rural population. Similarly, cutbacks in hydroelectric power generation because of prolonged drought results in loss of jobs and reduces the population's economic status. During dry periods, lack of food for humans and pasture for animals (domesticated and wild), often leads to mass migration of both in search of limited water and food resources. This, in turn, often leads to conflicts between humans and, also, between human and animals.

The African experience with weather: case studies

The 1997–98 El Niño is the best-documented and studied weather-related event ever and is sometimes called the 'El Niño of the 20th Century'. Glantz (2001), using lessons learned from this event, identified problems in coping with the impacts of El Niño, for example jurisdictional disputes among government agencies, the reliability of forecasts, lack of education and training about the El Niño phenomena, political and economic conditions (or crises) during the event, lack of resources to prevent or mitigate impacts, lack of donor sensitivity to local needs, poor communication, lag time between forecasts and impacts and between impacts and responses, responses and reconstruction, and so on. Many of these issues are not exclusive to coping with ENSO events, but apply to all kinds of natural hazards.

Sixteen countries participated in studying the impacts and responses to the major 1997–98 El Niño event, including Ethiopia, Kenya, and Mozambique (Glantz, 2001). Highlighted below are some of the impacts observed on various socioeconomic sectors/activities in Ethiopia and Kenya.

Ethiopia

The June–September 1997 seasonal rainfall totals in Ethiopia at 20 observation sites were 20% lower than in 1996. Almost all parts of Ethiopia had dry spells in the Kiremt months of July and August 1997. Of 33 zones in Ethiopia, the onset of rain in 18 zones was delayed, affecting land preparation and sowing. The 15 zones in which rains began well were affected by dry spells in the peak rainfall months of August and September; this adversely affected crop maturation.

Erratic rainfall reduced the area cultivated by 9% when compared to 1996; this was attributed to the low energy levels of oxen whose only grazing was sparse pasture. Poor farmers could not rent or borrow oxen at the right time because owners gave priority to their own plots. Plus, replanting several times because successive sowings failed as rains came and went depleted farmers' seed reserves. Yields were low because the land was not prepared properly and because the rains were poor and ceased early in the growing season. Lack of fodder reduced the price of cattle and some animals died, especially in the Raya region of northern Ethiopia. Production of coffee, the main cash crop, fell because coffee berries ready to be picked from the trees fell to the ground as a result of the heavy rains that came later in October and November. Food production declined after two good harvests in 1995–96 and 1996–97. Total output in the *meher* season in 1997–98 was reduced by 24% from 1996–97 levels. Prices of agricultural commodities increased by 13–53% compared with those of 1996.

Kenya

Heavy rains associated with the 1997–98 warm ENSO events had severe impacts on various socioeconomic sectors and activities in Kenya. These are highlighted below.

Water resources sector

The 1997–98 El Niño event had both negative and positive effects on the water resources sector. Negative impacts included widespread flooding that destroyed property in several parts of the country, increased soil erosion in areas with poor land use and management practices, and more frequent mudslides and landslides, especially in hilly areas with loose soil types. Other negative impacts included surface and groundwater pollution, destruction of small earth storage dams and high sedimentation and siltation rates in major reservoirs. The total cost of the damage was about US$9 million. However, on the positive side, the excess rainfall was a benefit. The heavy rain washed away pollutants, soil moisture for agricultural production was enhanced and the reservoirs were recharged, boosting output from hydroelectric power stations.

Agricultural sector

The agricultural sector was also both negatively and positively affected by the phenomenon. The abundance of rainfall resulted in a higher incidence of plant and animal diseases that depressed livestock and crop production in several regions in the country. Flooding also water logged farms, leading to a further reduction in yields and destruction of drinking points for livestock. Several cases of animals drowning were also reported. The estimated combined losses in this sector reached US$236 million.

However, in the arid and semiarid areas, the rains were a welcome relief from the perennial dry conditions; pastures improved, as did livestock production. Agricultural production in some areas was boosted due to greater availability of moisture for crops—more moisture was conserved in the soil and available to plants for a longer time. Survival rates of trees planted increased to nearly 100%.

Transport and communication sector

The El Niño rains devastated the transport sector. Floods and landslides wreaked havoc on roads and the transportation infrastructure throughout the country. Several bridges and an estimated 100,000 km of both rural and urban roads were destroyed, paralysing the transportation system in most parts of the country. The estimated cost of this damage was US$670 million. The aviation and shipping industries were also disrupted as their facilities were flooded. Scheduled and chartered flights were disrupted because of poor visibility and flooding—navigational equipment and runways were submerged. Docking facilities at the shipping ports were also submerged by floodwater, making it impossible to off-load merchandise from ships. Telecommunications were severely affected by falling trees that destroyed communication lines. Underground cable channels were also flooded, disrupting services. Electricity supplies were interrupted because equipment was destroyed by floods, falling trees and collapsed buildings.

Health sector

During the 1997–98 El Niño, Kenya's health services were pushed beyond their limits. Destruction of several health facilities, contamination of drinking water, an increase in the number of stagnant ponds, blocked and overflowing sewers and open drains, and a population explosion of flies breeding on decomposing refuse led to an upsurge in disease and higher morbidity and mortality rates. The heavy rains also saw the re-emergence of diseases, such as Rift Valley Fever that affected livestock in marginal areas.

The impacts on Africa of the 1998–2000 La Niña

During 1998–2000, southern Africa (including northern Mozambique and northern Madagascar) received abnormally low precipitation; the islands in the southwest Indian Ocean experienced the 'drought of the century'. In some drought areas, the aphid Cinara cupressi proliferated, and attacked and decimated many tropical conifers of the cypress group (Cupressus species). The gross domestic product (GDP) of countries in this region was affected by as much as 3.5% during this period. Rainfall deficits continued into 2001 along the east coast from northeastern South Africa up into Mozambique.

Failure of the rainy season in the Greater Horn of Africa (GHA) in 2000, following two years of erratic rainfall, triggered food shortages and losses of livestock not seen since the early 1980s. The widespread drought affected northern Kenya and southern Ethiopia most severely, but was also serious in Sudan, Somalia, the United Republic of Tanzania and Eritrea. This was also a time of civil strife and drought, and an estimated 20 million people faced food shortages in the GHA, 10 million of them in Ethiopia alone. The drought in parts of Kenya, Somalia, Mozambique and the United Republic of Tanzania continued into 2001.

In contrast, the 1998–2000 La Niña brought devastating floods to other parts of Africa. Heavy rains in the Sudan in 1999 damaged or destroyed more than 2,000 homes, while in Mozambique, some of the worst flooding in 40 years cost dozens of lives and massive property losses. Flooding recurred in Mozambique in 2000, partly due to La Niña, but exacerbated by Cyclone Connie in early February 2000. An even worse disaster, Cyclone Leon-Eline, struck shortly afterwards. By this time the region was already saturated, and the additional rainfall led to great loss of life.

2.5 Rainfall trends in Africa

Variability in rainfall is as much a characteristic of climate as the total amount of rainfall is (Gommes and Petrassi, 1994). Low rainfall, however, does not automatically lead to drought; nor is drought automatically associated with low rainfall. Agricultural drought, for example, arises when the supply of water is too low to satisfy the need of crops or livestock. In addition to lower-than-average rainfall, a number of factors—some not always obvious—may cause agricultural drought (Gommes and Petrassi, 1994). Although occasional widespread and severe climatological droughts catch the attention of the media, these 'invisible' agricultural droughts prevent subsistence farmers from achieving consistent and high yields. Such 'invisible' droughts are caused just as much by environmental degradation as by climatic factors (Gommes and Petrassi, 1994).

African droughts

Africa has a long history of fluctuations in rainfall which have varied in both length and intensity (Gommes and Petrassi, 1994). The most severe droughts were those of the 1910s, which affected both East and West Africa. These were generally followed by periods of higher rainfall. However, from 1950 onwards, rainfall decreased, culminating in a drought in West Africa in 1984 (Gommes and Petrassi, 1994).

Since 1988, good rains (frequently accompanied by floods) have fallen in the Sahel; some observers have interpreted these as the end of the Sahelian drought (Gommes and Petrassi, 1994). However, it is likely that rainfall will continue to vary, bringing 'good' and 'bad' years for rain. Despite this, some general regional patterns emerge: variability (between years and between seasons); trends (either upwards or downwards); and 'persistence'—a term which describes the fact that good and bad years do not occur randomly, but tend to occur in groups (Gommes and Petrassi, 1994).

'Good' and 'bad' years

Between 1960 and 1993, widely different rainfall conditions were experienced between years (Gommes and Petrassi, 1994). The 1960s tended to be the wettest, while the 1970s and 1980s were drier. Almost all of Africa experienced notably 'good', above-average rainfall in 1963 and, to a lesser extent, in 1989. However, three years in which rainfall was below-average or 'bad' were 1973, 1984 and 1992. Of these years, 1973 was the first bad one after a succession of good years. It therefore caught most countries unprepared. By contrast, the impact of the bad year in 1984 (in which rainfall was lower than in 1973) was relatively less severe because, by that time, many countries (especially those in the Sahel) had learned how to cope with bad years (Gommes and Petrassi, 1994).

In 1973 (and to a lesser extent in 1984) almost all African countries suffered bad years (Gommes and Petrassi, 1994). By contrast, the 1992 southern African drought was relatively limited in its geographical extent as the Sahel had one of its good 'post-1988' years (with average or above-average rainfall) (Gommes and Petrassi, 1994).

Agricultural drought

An agricultural drought is an extended period (days) with no rainfall when crop-water requirements (potential evapotranspiration) exceed the available moisture within the crop root zone. Seasonal changes in available soil moisture often occur at critical crop growth stages and hence affect crop productivity significantly (Biamah, 2005).

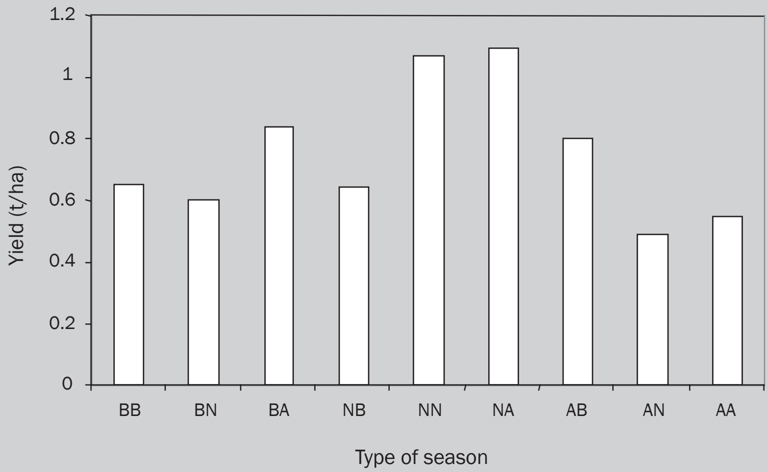
2.6 Climate change and its effect in Africa

The development agendas of many developing countries are increasingly being affected by climate-related disasters including drought, floods and landslides (DWC, 2003) largely because of increasing climate variability and associated risks. Rainfed agriculture accounts for significant subsistence food production in Kenya but is vulnerable to increasing climate variability and long-term climate change. Climate change may increase the risk of food insecurity in the country. Together with other factors, such as rapid population growth, poor management of natural resources and limited use of technologies, climate variability, or long-term climate change, could make poverty worse in Kenya. Because climate change may have many diverse impacts, a combination of approaches, including both technical and social strategies, will be needed to adapt to changes (Bergkamp *et al.*, 2003). Developing such a combination of approaches will only be possible if we take stock of current measures to address vulnerability to climatic variations and use this information to devise long-term adaptation strategies.

Box 4. Variable rainfall in rainfed farming

Background: The greatest challenge to rainfed farming is to deal with the variability in rainfall, both within and between seasons. Typically, rainfall during a crop season at many locations in the semiarid tropics varies from about a third to two-and-a-half times the average. For example, at Katumani, Kenya, rainfall records show that average seasonal rainfall during the driest years is about 35–40% of that during the wettest years.

The wide variation in seasonal rainfall presents both opportunities and challenges. As seasonal rainfall is highly variable and as farmers need to plan which crops they will grow before they know what kind of season will follow, farmers favor low-risk conservative management strategies that reduce negative impacts in poor years. These low-risk strategies reduce productivity and, therefore, profits, and use resources inefficiently, especially during favorable seasons.



Maize yield in Machakos, Kenya, during short and long rain seasons in years with different amounts of rainfall (B=Below-average, N=Normal, A=Above average)

Aversion to risk explains why farmers are slow to adopt technologies such as drought-tolerant varieties and escaping crops, in situ rainwater conservation techniques and ex situ water harvesting, and small-scale irrigation systems. Researchers have also developed a number of risk management strategies, including maintaining reserves of water in storage, insurance, forward selling, futures trading, government subsidies and taxation incentives. However, these interventions require good institutional and policy support which limits adoption in many developing countries in general, and in Africa in particular.

Opportunities: Farmers could consider changing their management practices if they had reliable advance information, such as the long-term/seasonal climate forecasts from the International Research Institute for Climate Prediction (IRI) and ICPAC (IGAD Climate Prediction and Application Centre formerly the Drought Monitoring Centre). Growing understanding of interactions between the atmosphere, sea and land surfaces, and advances in modeling the global climate system have contributed significantly to improving the accuracy and reliability of these long-term forecasts.

Climate variability is already having a significant negative effect on the region's socioeconomic development. This is likely to become more serious with climate change, hence the need to vigorously pursue adaptation strategies. Climate change is likely to compound the difficulties faced in the region: steadily declining agricultural yields and per capita food production, coupled with population growth, will double demand for food, water and livestock forage in the next 30 years.

High variability characterizes rainfall in East Africa. With climate change, parts of East Africa will become drier, significantly reducing the length of the growing season, while other parts, including southern Kenya and northern Tanzania, may become wetter, increasing the length of the growing season (Galvin *et al.*, 2004). Rainfed agriculture, which accounts for approximately 90% of subsistence food production, will become more risky with increasing climate variability and long-term climate change. In general, East Africa is expected to receive more rainfall but less surface runoff due to higher temperatures (Eriksen and Naess, 2003).

Climate change trends

Climate change projections to the year 2030 for Kenya indicate that temperatures will increase and CO_2 levels will double from baseline scenarios. Precipitation in semiarid areas (Government of Kenya, 2002) will decline and may lead to lower maize yields, a shortage of forage for livestock, a higher incidence of disease and a breakdown of marketing infrastructure. In Tanzania, the annual temperature over the whole country is predicted to increase by 2.5–3^{o}C in the warmest months, December–February, and by 3–3.9^{o}C in the coolest months, June–August.

Areas with two rainy seasons (the northeast, northwest, Lake Victoria Basin and the northern part of the coastal belt) may get 5–45% more rain in both seasons, while rain in areas with unimodal rainfall (southern, southwestern, western, central and eastern parts) may decrease by 5–15% (ibid).

In recent years, frequent and severe droughts have affected most parts of Uganda, although they have been more pronounced in the west and northeast of the country. Various models predict that temperatures will rise by 2–4^{o}C. The wettest district of Uganda is around Lake Victoria (Fig. 19). Apart from central Uganda, other parts of the country are expected to experience increasingly variable rainfall. A 10–20% increase in runoff is expected for most parts of the country, except for the semiarid areas where data is lacking and, therefore, the impact of climate change cannot be predicted (ibid).

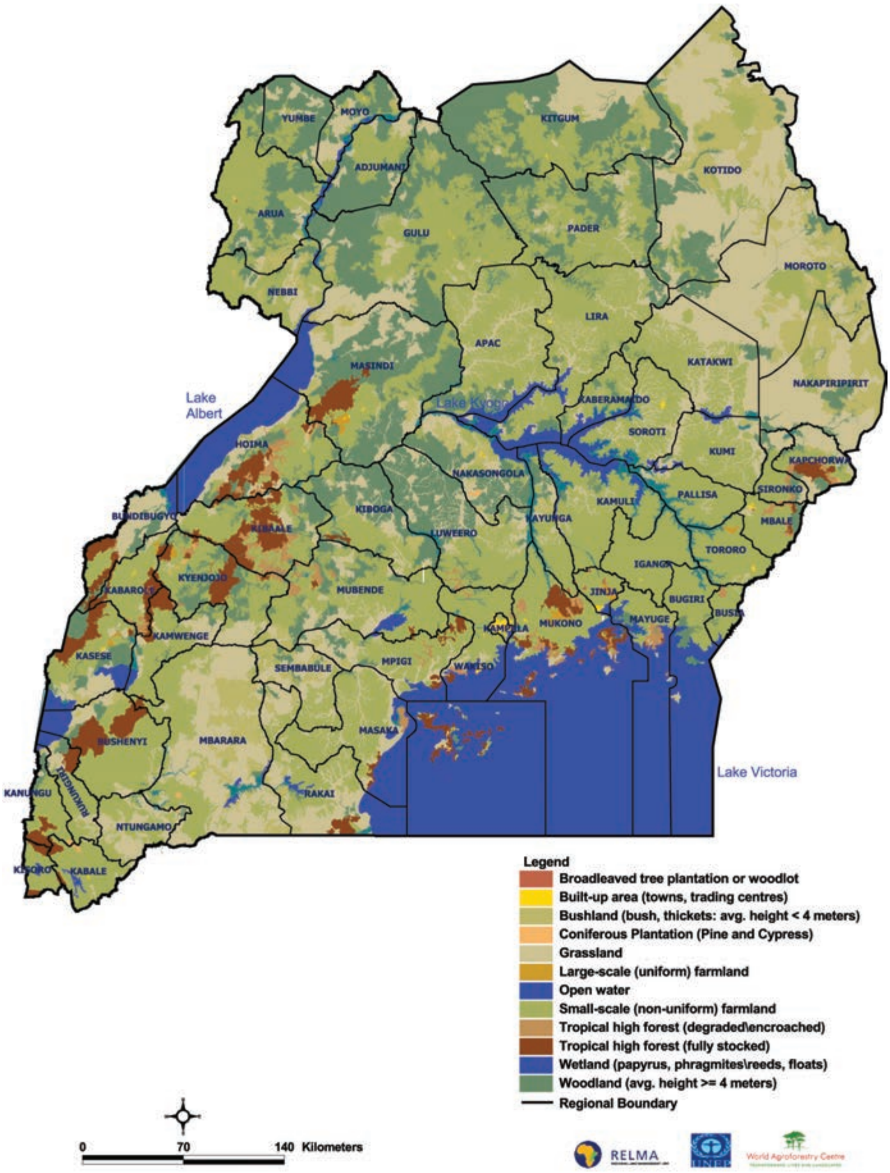


Figure 19: *Land use in Uganda*

Challenges and opportunities associated with climate change

According to Cooper (2004), the greatest impact on food security in the near future is more likely to come from drastic changes associated with climate variability than from gradual long-term climate change. Climate variability, in terms of the onset and cessation of rainfall is, and will continue to be, a serious risk for farmers in marginal areas of East Africa where agriculture is mostly rainfed.

Rainfall variability also has profound impacts on pastoral systems in East Africa (Galvin *et al.*, 2004). In dryland areas, pastoralism is often the only profitable farming system. For example, the cattle corridor in Uganda contains 60% of the livestock in the country, while dryland areas in Sudan contain over 100 million animals. Pastoralism is the best way of using the rangelands as pastoralists have their own strategies for dealing with variable climate, for example moving livestock to areas where forage and water keeping mixed herds to take advantage of the heterogeneous nature of the environment, and adopting diverse livelihood strategies—farming and engaging in wage labour (Galvin *et al.*, 2004). A number of strategies have been suggested to promote adaptation to climate change in the livestock sector, including reducing the livestock population, improving pasture/rangeland management, and rainwater harvesting. But, some of the options, for example reducing the livestock population, seem not to factor in the sociocultural and political environment in which these pastoralists operate.

Changes in temperature and precipitation could also bring new pests and diseases. For agriculture to remain profitable, the risks posed by new pests and diseases will have to be addressed by developing pest- and disease-resistant varieties and appropriate management systems. Livestock may be important reservoirs or hosts of disease vectors. Modelling climate scenarios may provide useful information on the potential effects of plant and livestock pests.

Many complex inter-related issues contribute to the current lack of investment in rainfed agriculture in SSA. However, there is one fundamental factor that cannot be ignored, and that is rainfall variability, both within and between seasons, and the uncertainty that it imposes on production. The evolution of coping strategies in farming and pastoral communities over the generations reflects this uncertainty. However, rainfall variability also impinges on the investment attitudes of other stakeholders who show an understandable reluctance to invest in potentially more sustainable and productive practices when the outcomes seem so uncertain from year to year.

Climate change will affect both water quantity and quality. In parts of East Africa, per capita water storage is already low and over-extraction of groundwater resources, increased competition and conflicts over water may become common. Water storage capacity needs to be improved to retain water and prevent floods in the rainy season. In pastoral areas, rivers and reservoirs dry up during severe water shortages and contribute to loss of livestock from hunger, thirst and disease, and conflict over limited grazing

Climate change will also make the task of providing sufficient water more difficult, because dry spells, droughts and floods are likely to occur more often, and at unexpected times. In addition, conflicts between competing sectoral uses of water, and between land use and terrestrial ecosystems upstream and aquatic ecosystems downstream, are becoming more common and threaten both the internal and external security of many nations.

2.7 Climate variability and change: coping strategies

Policies

The socioeconomic costs of climate change cannot be entirely eliminated, but timely and appropriate mitigation measures can certainly reduce the impacts. In fact, advance warning of El Niño episodes allows nations to plan for uncertainty, with considerable advantages to many sectors of the economy, such as water resources, tourism, and fisheries and agricultural production (Obasi, 1999). For example, in the case of the 1997–98 El Niño events, advances in monitoring sea-surface temperatures in the Pacific Ocean, enabled scientists in the National Meteorological and Hydrological Services to predict the formation of El Niño much earlier than previously. Developments in communication technology, including the use of the Internet, allowed information on the El Niño to be disseminated rapidly around the world. These early warnings enabled many governments to take appropriate measures, stimulated international cooperation and integrated efforts to address the ensuing impacts.

Following that major ENSO event, many African countries reflected on the experience they gained and their vulnerabilities, and put forward action plans for their governments, climate experts, citizens and media groups. For example, they highlighted the benefits of:

- better coordination between the various agencies responsible for early warning;
- better awareness of ENSO, and its characteristics and impacts, amongst government and other agencies and society in general;
- investing in monitoring networks and strengthening forecast capacity; and
- taking preventative action, when and where possible, based on climate data, local conditions and seasonal predictions.

Whereas the 1999–2000 drought in the arid and semiarid lands (ASALs) of eastern Africa was the most severe since 1961 (worse than 1984), its impacts were not as severe as those in the 1984 drought. This was mainly because governments of the affected nations used the forecasts provided by the National Meteorological and Hydrological Services to put in place mitigation measures to address the associated impacts.

The after-effects of a major climate-related event can undo years of development efforts. It is hoped that investments in education, communications, monitoring and prediction will help to mitigate the effects of future ENSO events on the nations of Africa.

Even though climate is a major determinant in water availability, management practice, policies and socioeconomic processes also determine access to water in many areas. In certain areas, people lack access to water not because it is scarce, but due to inappropriate policies. The water sector in East African countries, as in other regions of the world, is being reformed, decentralized and liberalized in the hope that these measures will improve the efficiency and delivery of water services (Orindi and Huggins, 2005). Such wide-ranging changes should be carried out gradually, and in consultation with users. Lessons learned from implementing such changes should be used to inform future management decisions.

Water resource management

Suggested strategies to help East African countries adapt to climate change include transferring water between basins, constructing reservoirs, increasing irrigation to boost production and encouraging the use of water-harvesting technologies. While such strategies could go along way towards improving water supplies some, including construction of reservoirs and interbasin water transfer, are expensive and should be undertaken by governments. At the household and individual level, other strategies should focus on low-cost technologies (e.g. rainwater harvesting) which could be implemented immediately with the limited resources already available

Ecosystem sustainability

Degradation of catchment areas results in less percolation, higher rates of runoff and more flooding downstream. The excess runoff, if harvested and stored, could make an immense contribution to economic activity; for agricultural production, for example, it would provide water for supplementary irrigation outside the rainy season to minimize the impact of rainfall variability within and between seasons. Sediment-laden flow from degraded watersheds/catchments, rather than being stored, is often diverted around reservoirs to avoid siltation. Soil and water conservation measures need to be stepped up to reduce the rate of soil erosion and improve soil-moisture storage. These measures will help strengthen the resilience of farming systems and ensure that they continue to be productive.

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Chapter 3

Classification of agricultural RWH systems

3.1 Overview

Definitions

Water harvesting is defined as the collection, conveyance and storage of rainwater for later use in the production of biomass (food crops, pasture and trees), livestock production and for domestic purposes. In sum, rainwater harvesting is the process of collecting and improving the productive use of rainwater, and reducing unproductive runoff. This often involves collecting rainwater from a catchment area and channelling it to cropping areas. In microcatchment systems, water is collected from land adjacent to growing areas, while in macrocatchment systems large flows are diverted and either used directly or stored for supplementary irrigation.

Rainfall has four facets: (1) rainfall induces surface flow on runoff areas, (2) at the foot of slopes, runoff collects in basin areas, (3) here, most infiltrates and is stored in the root zone and (4) after infiltration has ceased, the stored soil water is conserved.

Common terminology

- *Consumptive water use* is water consumption that withdraws or abstracts and uses water without generating any return flow. The water abstracted is no longer available for use because it has evaporated, been transpired, been incorporated into products and crops, been consumed by humans and livestock, or otherwise removed from freshwater resources. Losses of water during transport between points of abstraction and points of use (for example leakage from distribution pipes) are excluded from consumptive water use.

- *Ex situ rainwater harvesting* is the harvesting of run-off water in areas located outside the farming unit.

- *In situ site-based systems* are those in which all rainwater harvesting components are located within the farming unit.

- *Internal (micro) catchment rainwater harvesting* is where there is a distinct division between cropping area (CA) and catchment basin (CB) but the areas are adjacent to each other. This system is mainly used for growing crops such as maize, sorghum, groundnut and millet which need moderate amounts of water.

- *Non-consumptive water use* is the in situ use of water for navigation and for in-stream flow requirements for fish, recreation, effluent disposal and hydroelectric power generation.

- *Rainwater harvesting systems* are orderly schemes in which organized components and techniques harness and make rainwater available for human consumption and environmental conservation. Systems consist of six basic components: a collection area, a conveyance system, a storage facility, and filtering, treatment and delivery systems.

- *Water demand* is the volume of water requested by users to satisfy their needs. A simplistic interpretation considers that water demand equals water consumption. However, conceptually, the two terms cannot be equated because, in some cases, especially in rural parts of Africa, the theoretical water demand considerably exceeds actual consumptive water use.

- *Water productivity (WP)* broadly signifies the efficiency of water use at the production system or farm level. At this scale, the production of biomass per unit of water is expressed both in terms of the amount of crop produced per unit evapotranspiration *(ET)*, and in terms of the amount of crop produced per unit of rainfall/harvested water. Obtaining more crop per unit evapotranspiration implies a shift from non-productive evaporation to productive transpiration. Obtaining more crop per unit rainfall implies making maximum use of rain plus harvested surface runoff. The latter involves soil and water management.

- *Withdrawals or abstractions* involve taking water from a surface or groundwater source and, after use, returning the water to the same or another natural water body. An example is when industries abstract water for cooling and then return it to rivers. Such return flows into rivers are particularly important for downstream users.

Components of rainwater management systems for agriculture

All water-harvesting systems comprise catchment areas (sources of water), conveyance mechanisms, and provision for storage and application (Fig. 20). Catchments include natural slopes, sealed catchments, rocks, roofs, roads and rivers. Storage can be either short term or long term. Short-term storage is storage in or just above the soil profile, whereas long-term storage is deep ponding of water. Short-term storage is appropriate for crop, fodder, pasture and tree production, whereas long-term storage is appropriate to supply water for domestic use and livestock.

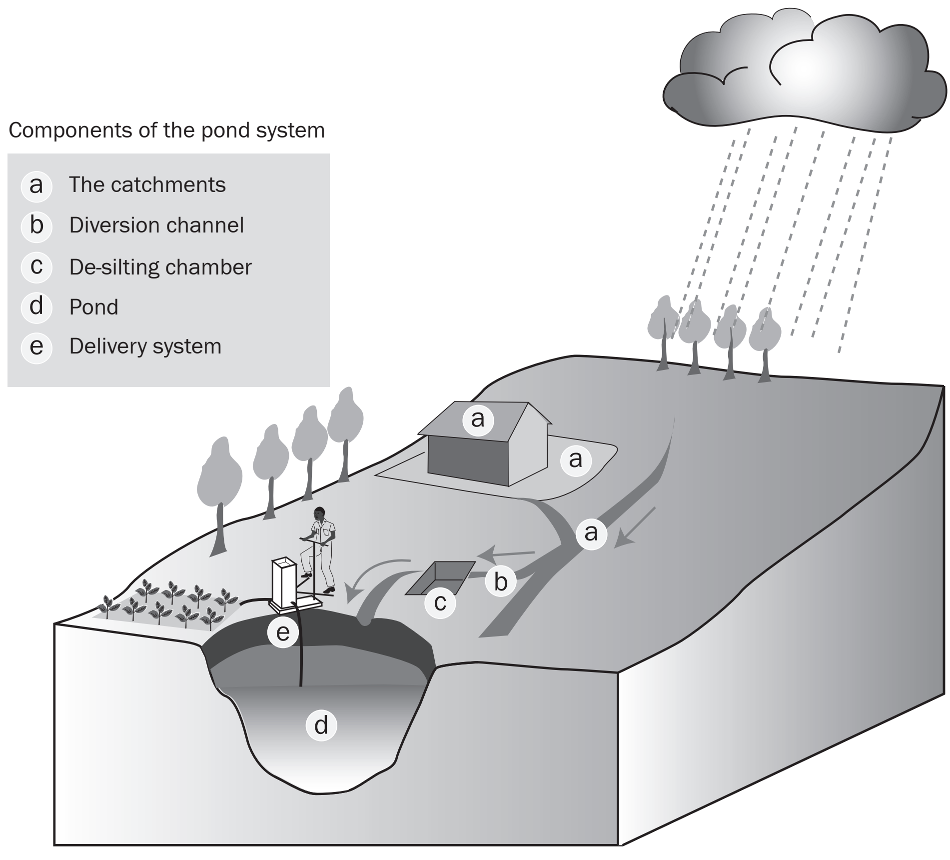


Figure 20: *Components of a rainwater management system*

3.2 Classification of rainwater harvesting systems

Rainwater harvesting systems are classified into two main groups on the basis of *size, site of catchment and source of water* (Fig. 21) and *hydrological and hydraulic (runoff) processes* (Fig. 22).

Catchment-based systems

Rainwater harvesting can be categorized according to the type of catchment surface used and, by implication, the scale of activity (Fig. 23).

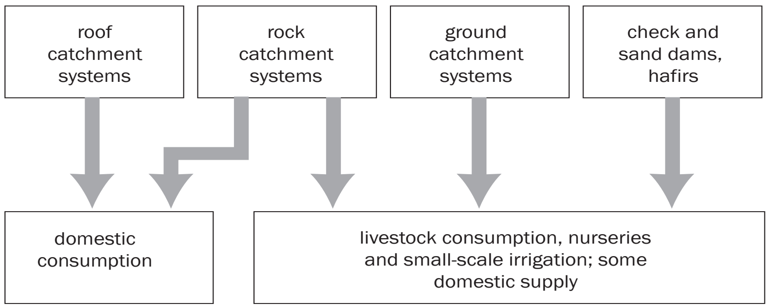
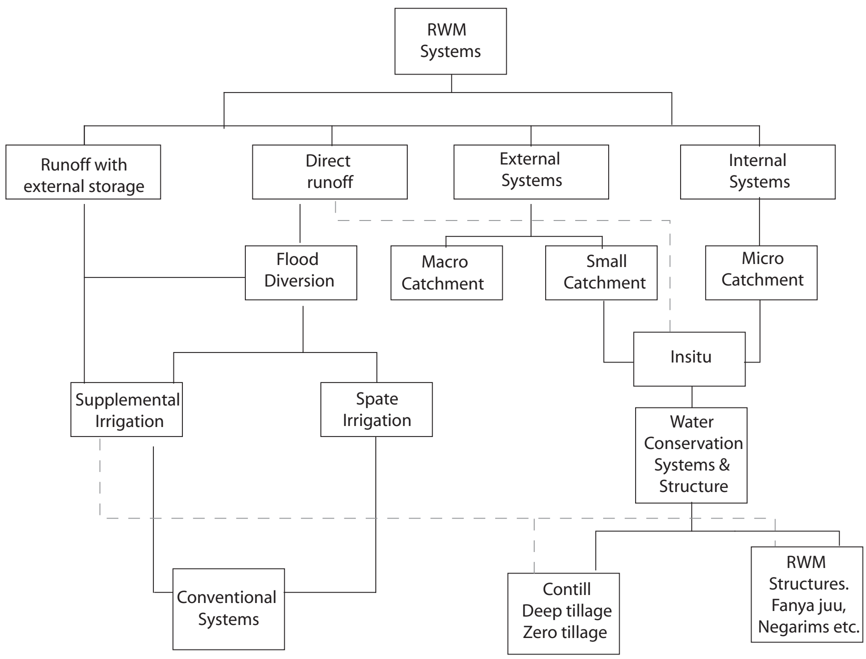


Figure 21: *Small-scale rainwater harvesting systems and uses (adapted from Gould and Nissen-Petersen, 1999)*



Source: Ngigi S. N.

Figure 22: *Classification of rainwater management (RWM) systems.*

Rainwater management systems can be further classified by regime:

- *Occasional*—Rainwater is stored in small containers for only a few days. Suitable where rainfall is regular—very few days without rain—and where there is a reliable alternative water source nearby.
- *Intermittent*—Used in situations with one long rainy season when all water demands are met by rainwater. However, during the dry season, water is collected from wells, springs and streams.
- *Partial*—In normal seasons, rain is used directly or water is drawn from other sources such as wells, springs and streams.
- *Full*—Rainwater provides water for all purposes throughout normal seasons. Usually, there is no alternative source of water. In these cases the available water should be well managed and enough stored to bridge the dry period.

The choice of regime depends on many variables, including the quantity of rainfall, the rainfall pattern (length of rainy periods, intensity of rains), available catchment area, available and affordable storage, daily consumption rate, number of users, cost and affordability, alternative water sources and the water management strategy.

Catchment classification can also be based on the location of the point source in relation to the location of the point of use. Such systems may be either external or internal systems depending on whether the catchment is external to, or within (internal), the cropped field.

External (ex situ) systems

Ex situ systems harvest flood water from catchments located outside crop land. They can either be macro (large) or small external systems:

Macrocatchment systems are large external catchments producing massive runoff (floods). This runoff is diverted from large fields, rocky surfaces, gullies and ephemeral streams to cropland. Techniques include diverting and spreading floods (spate irrigation), collecting water in basins and channelling it through canals. Macrocatchments with large storage structures could be used for large-scale and community-based projects.

Small external catchment systems (e.g. those involving road drainage or adjacent fields) use water from an adjacent, small catchment for cropping (Critchley and Siegert, 1991). They also include runoff storage structures that capture runoff, mainly from small catchments, especially for small-scale land users.

Internal (micro and in situ) systems

Microcatchment rainwater harvesting involves subdividing cropped land into microcatchments that collect and spread runoff on to adjacent cropped land without using any special structures. The runoff within a field is directed either to single plants (as in the case of fruit trees), or to clusters of plants or row crops. In the latter case, alternating catchment and cropped areas often follow the contours. Weeding to reduce surface evaporation and compaction to reduce infiltration in the source area increase runoff. In the cultivated area, loosening the soil increases infiltration. The ratio of catchment to cultivated area varies from 1:1 to 5:1 depending on the rainfall regime, soil properties and crop-water requirements. There have been attempts to promote this technique in the Baringo and Turkana Districts in Kenya. Research in semiarid areas of eastern Kenya has shown that it is possible to increase yields of most crops by 30–90% using this technique (Gibberd, 1993; Itabari *et al.,* 2000).

Techniques to increase moisture availability include:

- for single plants or tree crops (e.g. pawpaw or oranges), *negarims* in Kitui (Kenya), ridges, saucer basins, semicircular bunds, crescent-shaped bunds, catch pits and deep pitting; and
- for plots of crops (e.g. maize, sorghum) *chololo* pits in Dodoma (Tanzania), furrows, basins, and water spreading.

In situ rainwater harvesting aims to increase the amount of water stored in the soil profile by trapping or holding the rain where it falls. This may involve directing small amounts of rainwater to run off and collect in areas where it is most needed. In situ rainwater harvesting is sometimes called water conservation and basically prevents net runoff from a given area by retaining rainwater and prolonging the infiltration period. This system works best where the soil water-holding capacity is good and rainfall is equal to or more than crop water requirements. Here, collecting rainwater and allowing it to infiltrate and percolate rather than run off could improve the soil-moisture content.

Hydrological and hydraulic systems

Hydrological and hydraulic systems (collection, conveyance and storage structures) harvest and conserve runoff. These systems collect runoff either at the field scale or from external catchments and direct water into the soil profile or store it for supplemental irrigation. Extensive research carried out in a semiarid area, on what are known as '*meskat*' systems, by the Soil and Water Management Research Group at Sokoine University, Morogoro, Tanzania, suggests that these systems improve yields significantly on the areas that receive runoff. Hydrological and hydraulic systems can be classified further as runoff with external storage and runoff with direct application.

Runoff systems with external storage

The performance of these systems depends on rainfall distribution, water needs and storage capacity.

Box 5. Capturing runoff

In runoff systems with external storage, runoff is collected from grazing land, uncultivated land, cultivated land and road drainage and directed into small manually constructed reservoirs (50–200 m^3). The stored water is then used for supplemental irrigation and for irrigating tree nurseries. Rainwater harvesting storage systems offer the land user a tool for controlling water stress and mitigating the effects of dry spells. They reduce risk of crop failure. Reservoirs should be located downstream of catchments and, preferably, upstream of cropland to take advantage of gravity to deliver the water (Rockström, 2000), thus minimizing energy requirements.

Rainwater harvesting systems with external storage are becoming popular for supplemental irrigation in semiarid districts of Kenya (e.g. Machakos, Laikipia and Kitui). They have also been introduced in Ethiopia (near Nazareth) on an experimental basis by RELMA. Moreover, small storage systems are common in parts of Ethiopia (e.g. Tigray) and in other regions of Africa. Initial results from rainwater harvesting experiments in Machakos District (Kenya) that focused on the feasibility of using earth dams to collect water for the supplemental irrigation of maize, have been encouraging (Rockström *et al.*, 2001). The main challenge with these systems is to design simple, cost-effective reservoirs and gravity-fed distribution systems to reduce the cost of lifting water.

In the semiarid parts of Laikipia District (Kenya), underground water tanks (50–100 m^3) have been promoted, mainly for kitchen gardening. The tanks are usually lined with polythene, mortar, rubble, stones or clay to reduce seepage losses. Covering the tanks with local material (thatch or iron sheets), minimizes evaporation.

Small-scale farmers in semiarid districts of eastern Kenya also use rock catchments/dams, sand dams and sub-surface dams (Gould and Nissen-Petersen, 1999; Pacey and Cullis, 1986). Sand dams and sub-surface dams are barriers constructed along sandy riverbeds to retain water—and are common in most semiarid environments. Such systems have provided water for decades, especially in Machakos and some parts of the Kitui District. They have also been introduced in the Dodoma area of Tanzania where, however, their potential has not been realized.

Farm ponds are also used for watering livestock. Communities construct earth dams and water pans to store large quantities of water, specifically for livestock and small-scale irrigation. These water pans and earth dams are vital for livestock in the arid and semiarid lands (ASALs) of Kenya, Somalia, and southern and northeastern Uganda. Earth dams were introduced by white settlers, whereas water pans are traditional sources of water, for example the *hafirs* (water pans) in the northeast of Kenya, parts of Somalia and western Sudan. Concrete/mortar-lined underground tanks (100–300 m^3) supply water for domestic use and for some livestock (milking cows, calves and weak animals separated from the main herds) in Somaliland.

Auxiliary facilities used with runoff and external storage systems. Stored water from storage tanks can be siphoned off by gravity, pumped into channels or pipes and directed to fields (Fig. 23).

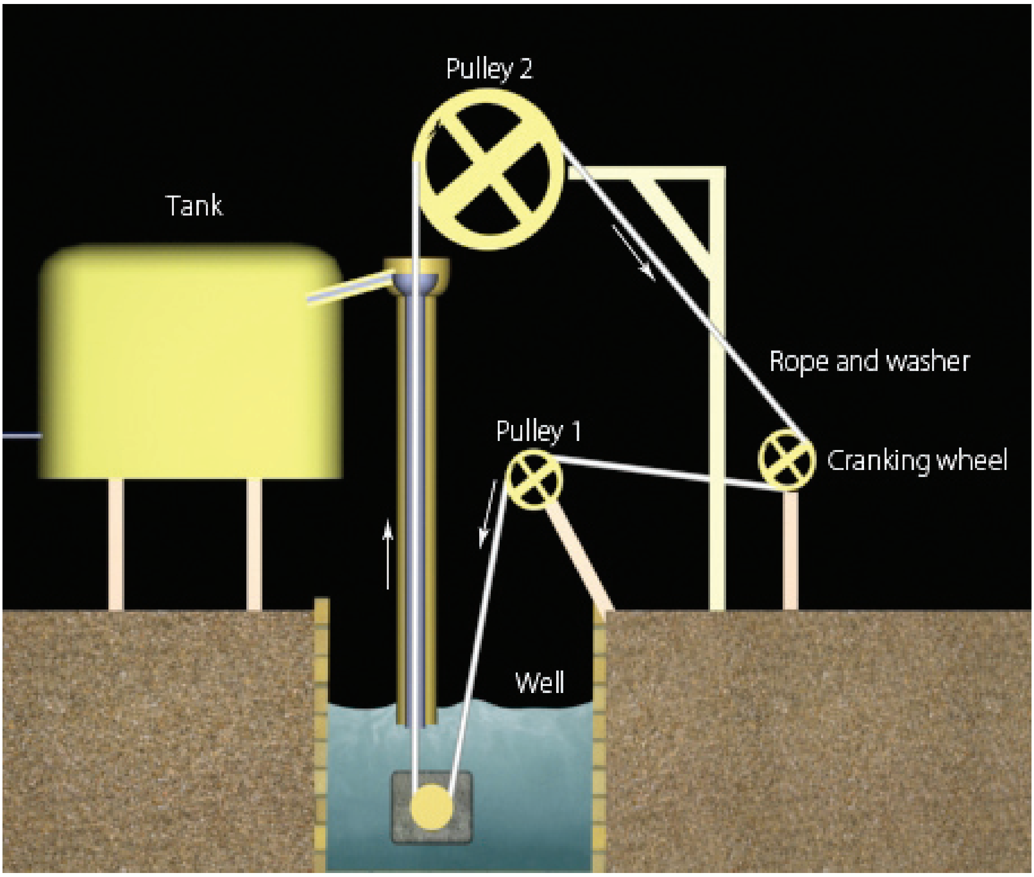


Figure 23: *Rope and Washer pump*

Piped distribution systems are potentially more efficient than traditional open channel networks. Piped systems distribute water to field hydrants or outlet boxes. From these, water is conveyed to crops in open channels, portable pipes, or hoses such as lay-flat hose. Final delivery to plants may be through gated pipes but water is still applied using surface irrigation techniques. Simple technologies, such as sprinkler or drip irrigation, and rainwater augmentation structures, such as terraces and *negarims*, could also be used to deliver water to crops.

Common devices to lift water into conveyance systems include:

- hand operated pumps, for example the rope and washer pump;
- foot pumps, such as the treadle pump; and
- buckets for withdrawing water directly.

Runoff systems with direct application
This category of rainwater harvesting system is characterized by components to generate runoff, and divert and spread it over cropland, where the soil profile acts as a moisture storage reservoir. Runoff may be collected ex situ (from external catchments) or in situ (from within the cropped field or internal catchment).

In situ rainwater runoff conservation technologies differ from ex situ runoff systems in that they do not include an external runoff generation area, but instead aim to conserve rainfall in the cropped area or pasture where it falls. The most common in situ rainwater runoff conservation technology is conservation tillage, which aims to maximize the amount of soil moisture in the root zone. A number of agronomic practices to conserve moisture, such as mulching, ridging, and adding manure, could fall into this category. Small field/farm structures, such as tied ridges/bunds within cropped areas that conserve direct rainfall—areas that have no 'external' catchment area outside the field boundary except runoff from upslope—also fall into this category. Examples are cropland or pasture contour bunds/ridges, bench terraces and sweet potato ridges in the Rakai District of Uganda.

In situ rainwater conservation is one of the simplest and cheapest rainwater conservation technologies and can be practiced in almost all land-use systems. In situ water conservation systems are by far the most common (Rockström, 2000) and are based on indigenous/traditional systems. The primary objective has been to control soil erosion and hence manage the negative side effects of runoff—soil and water conservation ensures minimal runoff. However, managing the negative effects has the positive effect of concentrating rainfall in cropped areas. In semiarid areas, especially where soils are coarse textured (for example the sandy soils common in the ASALs), and have high hydraulic conductivity, in situ conservation offers little or no protection against rainfall variability—the risk of crop failure is only slightly lower with in situ rainwater conservation than without. However, other measures, such as applying manure, could enhance yields.

In situ water conservation could also be considered as part of the soil profile storage systems, since direct rainfall that falls into the soil is stored, but not the surface runoff (Fig. 24). This increases water supply for cropping purposes in arid and semiarid regions. It promotes improved management practices in the cultivation of corn, cotton, sorghum, and many other crops. It also provides additional water supply for livestock and domestic consumption. This technology is applicable to low topographic areas in arid or semiarid climates.

Advantages of in situ rainwater harvesting:

- In situ technologies require minimal additional labour.
- In situ rainwater harvesting is flexible; furrows can be constructed before or after planting.

- In situ rainwater harvesting allows better utilization of rainwater for irrigation, particularly in the case of inclined raised beds.
- In situ rainwater harvesting is compatible with agricultural best-management practices, including crop rotation.
- In situ rainwater harvesting provides additional flexibility in soil utilization.
- Permeable in situ rainwater harvesting areas can be used to artificially recharge groundwater aquifers.

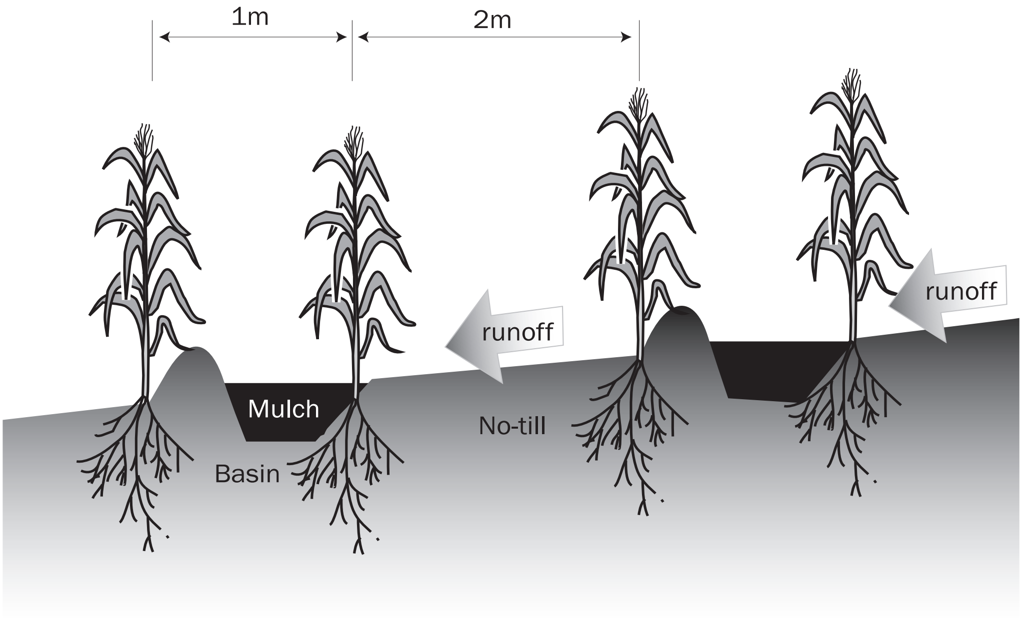


Figure 24: *In situ rainwater harvesting*

Disadvantages of in situ rainwater harvesting:

- In situ rainwater harvesting cannot be implemented where the slope of the land is greater than 5%.
- In situ rainwater harvesting is difficult to implement in rocky soils.
- Areas covered with stones need to be cleared before implementation.
- The costs of implementing this technology may discourage some farmers.
- In situ rainwater harvesting requires impermeable soils and low topographic relief in order to be effective.
- The effectiveness of the storage area can be limited by the evaporation that tends to occur between rains.

Integrated systems

The classification of rainwater harvesting systems is complicated by the fact that farmers may integrate or combine several technologies. For example, farmers practicing conservation tillage in Laikipia District also collect and spread runoff from small external catchments, such as roads/footpaths and adjacent fields. Farmers also direct runoff from external catchments onto cropland and collect rainwater in farm ponds for supplemental irrigation. In situ water conservation may also be combined with direct runoff systems on farms with terraces. Here, terrace channels (mainly '*fanya juu*' and contour ridges/bunds) collect and store runoff from small external catchments, while direct rainfall is harvested and conserved on the cropland between the channels. However, excess runoff generated from the cropland between the terrace channels will also be collected in the channels.

It is evident that the three groups of water harvesting techniques are appropriate for different geographic settings. Topography, runoff surface, infiltration rate, soil type of run-on areas and the depth of the soil layer in cropping areas are among the most important natural parameters to consider when implementing any water harvesting system. Additionally, socioeconomic factors have to be taken into account.

3.3 Survey and site selection

Before selecting a specific technique, due consideration must be given to social and cultural circumstances as these are vital to success or failure in the area of concern. This is particularly important in the arid and semiarid regions of Africa, where lack of consideration for community priorities may help to explain the failure of so many projects. In arid and semiarid regions of Africa, most of the population are subsistence farmers who, over the centuries, have set their priorities to address their basic needs for survival. Until these basic priorities have been satisfied, no lower priority activities can be effectively undertaken.

In addition to socioeconomic considerations, water harvesting schemes will only be sustainable if they also fulfil technical selection criteria. Rainwater harvesting for agriculture and ecosystem sustainability needs to be seen as part of an integrated system to meet the overall water requirements of a household, community or watershed. Project planning must take a people-centred approach and consider socioeconomic, cultural, institutional and gender issues, as well as perceptions, preferences and abilities. Factors for success in rainwater harvesting are:

- starting small and growing slowly to allow for testing and modification of the design and implementation strategy;
- clear expression of the demand for water;
- full involvement of both genders in all project stages; and
- substantial contributions from communities in ideas, funds and labour.

In a number of countries (e.g. Kenya, Fiji) women's groups have been very successful in financing and building their own rainwater harvesting tanks. However, management by individual households is most successful. This is because the user (often a woman) operates and controls the system, is responsible for its maintenance, manages the use of water (minimum misuse) and appreciates the convenience of water next to her/his home.

Investment costs vary considerably from country to country, mainly due to variations in the price of construction materials. The initial cost per capita is relatively high compared to alternatives (if available) but recurrent costs are relatively low. Economies of scale for storage are substantial; the larger the tank the lower the price per cubic meter. For example, in Kenya in 1998, the cost of a storage tank (per m^3) varied from US$21, for a large 90 m^3 underground ferro-cement tank, to US$126 (for a 4.6 m^3 plastic tank).

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Chapter 4

Technical issues and technological options

4.1 Crop production and rainwater management systems

4.1.1 Crop physiology and rainfall partitioning

Plant leaves photosynthesize using sunlight and carbon dioxide from the atmosphere and plant roots extract water and minerals—mostly essential but some not essential or even toxic—from the soil. Feedback mechanisms control relationships between the above- and below-ground parts of the plant in both unstressed and stressed environments. As roots grow, plant access to water and nutrients increases, thereby enhancing plant production or plant survival under water- or nutrient-limiting conditions. The shape and extent of root systems influence the rate and pattern of nutrient and water uptake from the soil. Root activities alter the pH, microbial population, chemical constituents and structure of the soil. At the same time, root configuration is influenced by nutrient and water availability, and other environmental factors such as soil temperature and soil mechanical strength. Temperature indirectly affects many root growth processes and root interactions with the surrounding 'rhizosphere' (root environment). In turn, plants shade the soil and transpire, thus moderating soil temperatures by altering the energy balance.

Root system shape and size

Clearly, the shape and extent of root systems influence the rate and pattern of nutrient and water uptake from the soil. However, studies have also shown that root configuration is itself influenced by nutrient and water supply. For example, when plants are deficient in nitrogen, their roots branch more where soil is locally enriched with nitrogen fertilizer. Studies of nutrient transfer to single or widely spaced roots have shown that resistance to nutrient transfer within the soil can reduce the rate of uptake. Hence, knowledge of the configuration of root systems is important for understanding water and nutrient uptake. Other factors affecting root system morphology and distribution include plant genetics, growth stage, soil chemistry (pH, salinity and concentration of toxic elements), soil water content, oxygen concentration, mechanical resistance and soil temperature. However, information on the effects of many of these variables is often lacking, and the mechanisms by which they operate are largely unknown. The complex interplay of root systems, soil and the atmosphere controls the transfer of nutrients, and natural and man-made pollutants, between the soil, plants, and groundwater or drainage water—often exposing humans and animals to toxins.

Root architecture and root responses to various soil conditions are of pivotal importance in evaluating plant growth, under both current and potential changing climatic conditions. Interaction between roots and soil in the rhizosphere can control the quantity and quality of groundwater transport between the soil surface and the saturated zone.

Pathways of water in roots

Uptake of water by plants is driven by gradients in water potential along a pathway that links soil, roots, foliage and atmosphere. Water potential decreases continually from soil to atmosphere.

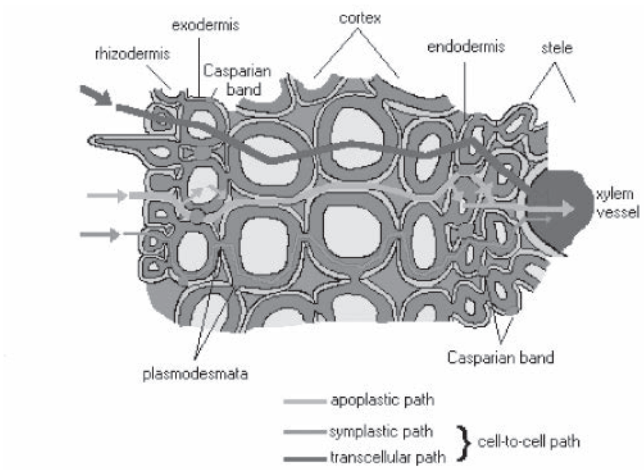

Figure 25: *Pathways of water in roots*

Evaporation within the substomatal cavities of leaves creates tension in the continuous column of water that connects leaves to root tips. Water moves into roots when the water potential is lower in roots than it is in the soil.

Relationships between flow and the drop in water potential (γ) along the uptake pathway can be represented as an Ohm's Law analogue. The hydraulic properties of each segment of the flow path are modelled as a transport coefficient known as the hydraulic conductance, k (the inverse of the resistance to flow). Flow along all parts of the pathway is equal to the rate of evaporation from the leaves (E), and is related to gradients in potential between the soil γs, root surface γrs, base of the stem γb and leaf γl.

$$E= (\gamma s- \gamma rs)\, Ks= (\gamma rs- \gamma b)\, Kr \ldots\ldots\ldots (i)$$
$$= (\gamma b- \gamma l\, \gamma)\, Ksh$$

Where Ks, Kr and Ksh are hydraulic conductances for the soil, root system and shoot respectively.

Shrinkage of roots in very dry soil can create an interstitial resistance to uptake, causing a sharp decline in Ks. When expressed per unit root length, Kr becomes root hydraulic conductivity. As defined here, Kr combines the components of conductivity for radial transport across the root, from the root surface to xylem, and axial transport to the base of the stem. Soil hydraulic conductivity Ks can also be expressed per unit root length. The rate of uptake of water (S) by a root system of root length density Lv and occupying soil volume V is then given by:

$$S=(\gamma s-\gamma b).LvV/(1/Ks+1/Kr)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(ii)$$

Unless roots are very sparse, S is most limited by Kr at soil water contents above the wilting point. Uptake from soil with water potential s is therefore dependent on the water potential within the plant, the hydraulic conductivity of the root system and the density of the root network.

4.1.2 The crop water balance

The water balance of agroecological systems is a key parameter for most physical and physiological processes in the soil–crop–climate system. One of the most critical factors is evapotranspiration (ET); ET has a great impact on water losses, depending on various complex factors. The methods for calculating potential evapotranspiration (ETp) can be very simple (empirically based), requiring only monthly average temperature data, or very complex (physically based), requiring daily data on maximum and minimum temperature, solar radiation, humidity and wind speed, as well as vegetation characteristics.

The crop water balance in savanna agroecosystems can be expressed as

$$P + Irr + R_{on} = R_{off} + (E+I+T) + D + \Delta S$$

Where:

P=Rainfall

Irr= Irrigation

R_{on}*=Run-on from adjacent upslope land*

R_{off}*=Runoff from field*

E=Evaporation

I=Interception losses

T=Transpiration losses

D=Deep percolation

ΔS*= Change in water content in soil during time step*

(E+T+I)=Green water flow. Amount of water used or required for production of biomass.

Atmospheric demand (ETp) ranges from 1.5 to 10 times the annual average rainfall in the semiarid tropics. At the field scale, large amounts of water are not used productively, i.e. they are lost through evaporation, runoff and deep percolation (E, R_{off}, D); less is used productively and released to the atmosphere through transpiration The long-term seasonal amounts of water lost without being used productively often range between 400 and 1,000 mm, concentrated in a limited period of 70–140 days. This substantial amount of water could hypothetically produce 4,000–10,000 kg grain/ha if used effectively for transpiration. Crop-water deficits are not so much due to lack of rainfall but to poor distribution of rainfall. Rainfall is usually heavy and causes floods, soil erosion and damage to infrastructure. Actual crop water stress will depend on rainfall partitioning.

Estimating effective rainfall

Factors that influence effective rainfall are soil slope, soil texture and structure, plant cover or crop residue cover, and storm intensity and duration. Effective precipitation is important in rainwater harvesting for agriculture and is a guiding factor in planning crop production. The components of rainfall are runoff, infiltration, interception (rainfall that is caught on the plant surfaces) and evapotranspiration (ET). The proportion of rainfall that leaves a field as runoff can be estimated based on cropping practice, soil characteristics, pre-rainfall moisture status and the amount of rainfall. Likewise, the proportion of infiltration can be calculated from estimates of runoff and the measured amount of rainfall. The amount of moisture in the root zone before rain falls influences how much is stored in the root zone and how much percolates through.

Infiltration is estimated by subtracting the amount of runoff from the amount of rainfall measured in the rain gauge. Infiltrated water can either recharge the soil profile or, if the profile cannot hold the infiltrated water, the excess percolates below the root zone. If the depth of infiltration is greater than the depth of the root zone, the part of the soil profile used by plants is fully replenished. If the amount of water the root zone can hold is greater than the amount that has infiltrated, the effective rainfall equals the infiltrated depth.

The variability of field conditions is a challenge to estimating effective rainfall, and irrigation scheduling in general. The amount of rainfall varies across each field, but often there is only one rain gauge to measure rainfall over the whole field. Other variables include soil texture, infiltration rates, slope, plant residue cover and soil depth. When making decisions concerning effective rainfall or irrigation schedules, it is customary to consider the dominant conditions. If most of a field is flat, and only a small portion slopes severely, decisions would usually be made based on the flat areas. If relatively large areas have dramatically different conditions, decisions could be made separately for each area. If one decision is made for both areas, a conservative approach (least yield reducing) is appropriate.

4.1.3 On-farm technologies for crop production

Enhance rainfed production

Rainfed agriculture produces by far the highest proportion (over 60%) of food crops in the world. If animal forage is included, the contribution of rainfed agriculture to food and commodity production is very high indeed. In Sub-Saharan Africa it is estimated that over 90% of agricultural production is rainfed. Yet, water resource planning for agriculture has largely neglected rainfed production. Irrigation in Sub-Saharan Africa has been tried, but only a limited effort has been directed to upgrading rainfed agriculture by improving water-use effectiveness.

Research has shown that in the semiarid tropics (SAT) often only a small fraction of rainwater reaches and remains in the root zone long enough to be useful to crops. It is estimated that, in many farming systems, more than 70% of the direct rain falling on a crop field is lost as non-productive evaporation, or flows away into sinks before plants can use it. It is only in extreme cases that as much as 4–9% of rainwater is used for crop transpiration (usually the percentage is lower). Therefore, in rainfed agriculture, rainwater wastage is a more common cause of low yields, or complete crop failure, than absolute shortage of cumulative seasonal rainfall. This is demonstrated by experience in the USA. Adoption of improved water conservation technologies in the central Great Plains is said to have made the largest single contribution (45%) to the increase in average wheat yields, significantly ahead of improved varieties (30%) and improved fertilization (5%). Furthermore, unreliable supplies of water for plant growth are perhaps one of the key reasons that the Green Revolution did not happen in Sub-Saharan Africa.

Soil and water conservation (SWC) technologies to overcome loss of water in rainfed agriculture are well known. The principle requirements are to improve infiltration, water-holding capacity and water uptake by plants. For example, it has been shown that sub-soiling, coupled with application of manure, quadrupled yields of maize per unit of land in dry areas of Tanzania. There are, therefore, win–win benefits in converting erosive runoff into soil-water available to plants, and non-productive evaporation to productive transpiration. The production of plant dry matter often has a linear correlation with seasonal transpiration, while the amount of available water taken up by plants is dependent on the extent to which roots are in contact with water. However, in some areas, even capturing all the rainwater where it falls may not be enough. This then calls for rainwater harvesting.

Rainwater harvesting

Experience in Tanzania, for example, shows that farmers are aware that both crop and livestock production can be improved substantially by concentrating scarce rainwater where it is needed, as well as by supplementary irrigation at critical stages of plant growth. Such measures allow them to produce crops with a high water demand. This strategy is demonstrated by *mashamba ya mbugani* (fields at low points in the landscape). Farmers grow high water demand crops, such as vegetables, rice and maize, in the lower parts of the landscape. The aim is to exploit the natural concentration of rainwater and nutrients flowing into valley bottoms from surrounding high areas. Furthermore, a survey of innovations adopted by farmers in semiarid areas of Tanzania, Kenya and Uganda found that 30% were rainwater harvesting innovations, 20% were soil-nutrient management innovations and 4% were forestry innovations. In total, water management innovations constituted 50% of all innovations.

In the semiarid areas of Tanzania, the *mashamba ya mbugani* practice has been improved for the cultivation of paddy rice in the SAT. The improved technology involves the construction of water storage reservoirs to concentrate and store high volumes of water for extended periods. As well as capturing and storing rainwater where it falls, the improved technology provides for the supply of extra water from external catchments. Paddy fields are constructed on relatively flat or gently sloping terrain by building bunds, 0.3–0.7 m high, around the field perimeter. The environment created is only conducive to the cultivation of paddy rice. For this reason, farmers have converted from cultivating sorghum and millet, to cultivating rice.

This system is now widely used in nearly all the semiarid areas in central Tanzania and accounts for over 70% of rice cultivation and more than 35% of rice production in Tanzania. Farmers can now grow a marketable crop in dry areas, providing opportunities for poverty reduction. Research has shown that gross margins improve significantly when farmers adopt this technology. Paddy rice is now a SAT crop in Tanzania, as a result of improved management of rainwater.

The potential for wide adoption of water concentration practices in many other SAT areas is huge because, in most of these areas, continuing erosion and deposition has created very fertile areas at the bottom of topo-sequences. The great potential of these areas has yet to be utilized. Vertisols are estimated to cover some 55 million hectares in the semiarid areas of Chad, the Sudan, Ethiopia, Kenya, Tanzania and 11 other countries in Sub-Saharan Africa. Most vertisols are inherently fertile as they lie in the lower parts of the landscape where floodwater and nutrients accumulate each season. However, because they are difficult to manage they are largely unutilized. Therefore, the sustainable use of vertisols presents one of the leading technological challenges in the development of the SAT region. Addressing this challenge will require improved control and management of the available water.

Precision irrigation

The rainwater harvesting approaches described in the previous section are dominated by the classical approach of periodic flooding to saturate the entire field. This approach often leads to high evaporation from soil and water surfaces, and low water productivity. Water productivity can be improved by introducing precision irrigation. This involves applying precise quantities of water to the root zone when required. This includes, for example, application of a small amount of water during a dry spell to overcome plant stress at a critical growth stage. Technologies for achieving high levels of control are already available. One example is the micro-drip technique for high frequency, low volume application of water and nutrients to specific crop areas.

Precision irrigation reduces unproductive depletion of water from the soil. Applying water directly to the root zone increases transpiration—due to improved contact between water and roots—and reduces soil evaporation and deep percolation. This increases water productivity. Furthermore, improved control over the timing of application makes it easy to implement supplementary irrigation strategically to overcome seasonal dry spells. Work has showed that water productivity in rainfed wheat production in Jordan could be increased from 0.33 kg/m^3 to 3 kg/m^3 by strategic supplementary irrigation.

Modified (enlarged) fanya juu terraces

Fanya juu (*juu* is the Swahili word for 'up') are so called because, during construction, soil is excavated and thrown up slope to make an embankment. The bank prevents runoff, while the trench (canal) is used to retain or collect runoff (Fig. 27). The trench is dug along the contour to ensure that the collected water is retained and does not flow away. Conventional *fanya juu* canals are usually 0.6 m deep and 0.6 m wide. Enlarged *fanya juus* are about 1.5 m deep and 1 m wide. Often, runoff from external catchments (roads, homestead compounds or grazing land) is led into the canals, which act as retention ditches and allow water more time to infiltrate the soil. Crops, such as bananas, pawpaws, citrus and guava, are grown in the ditches. This technique is widely practiced in the Machakos and Kitui Districts of Kenya, and has proven effective in harvesting water on slopes greater than 5% where other water harvesting techniques are not recommended.

Whereas *fanya juu* were previously used with diversion/cutoff drains for soil conservation, they have now been adapted for rainwater harvesting by constructing planting pits—mainly for bananas—and tied ridges (check dams) for controlling runoff. Outlets are blocked to retain runoff and spillways discharge the excess, which is then diverted onto lower terraces. In southern Uganda, a similar system has been adopted—contour ridges/bunds (shallow *fanya juu* terraces) with tied ridges at regular intervals—for banana plantations. The runoff from hilly grazing land is distributed into the banana plantations by contour ridges. Agroforestry (for firewood and fodder) is also incorporated, where trees are planted on the lower side and Napier or giant Tanzania grass along the ridges.

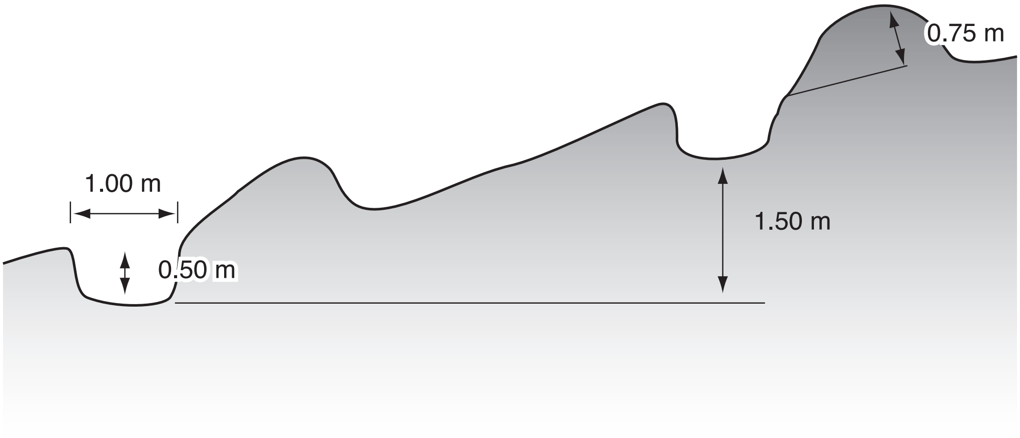

Figure 26: *Fanya juu*

In eastern Sudan, a traditional system of harvesting rainwater in 'terraces' is widely practiced for growing sorghum. Earthen bunds with wing walls impound water to depths of at least 50 cm. Within the main bund there may be similar smaller bunds which impound less runoff and where crops can be planted earlier. *Fanya chini*, in which the soil is thrown downslope instead of upslope, were developed in the Arusha region of Tanzania.

Road runoff with canals

This technique involves diverting road runoff into a canal network on the farm. Canals are about 1.5 m deep, 1 m wide and spaced about 2 m apart. This system—also called banana canal because bananas are invariably planted in the canals—is being practiced on slopes of more than 5%, mainly in Kitui, Machakos and Mwingi Districts. While bananas are planted in the canals themselves, fruit trees such as pawpaw are planted in between, together with vegetables, such as beans, during the rainy season.

Runoff from hillsides and rocks

Runoff from rocky surfaces and hillsides can be channelled into large basins created by building bunds (Critchley and Siegert, 1991). Research in the Baringo District, Kenya, showed that rainfall of as little as 8 mm produced surface runoff because of the highly impervious hillsides. In field trials using a runoff harvesting system with a catchment size of one hectare, 48% of showers greater than 10 mm produced sufficient runoff to flow into bunded basins. This means that field crops, such as sorghum and millet, could be grown in otherwise very arid conditions.

Basins

Earth basins are normally well-levelled small, circular, square or diamond shaped microcatchments, constructed to capture and hold all rainwater that falls on a field or diverted runoff from roads. The principle is similar to surface irrigation. Basins are constructed by making low earth ridges on all sides to retain rainfall and runoff in the mini-basin. Runoff is then channelled to the lowest point and stored in an infiltration pit.

The size of basins varies from 1 m to 2 m in width and up to 30 m in length for large external catchments. The embankments are about 20–30 cm high and 30–45 cm wide. The main limitation is the need to use a large area of land relative to the crop area. There is also the danger of the embankments breaching in the event of unexpectedly high rainfall.

Earth basins are suitable for dry areas where annual rainfall amounts to at least 150 mm, the land is flat or slopes up to 5%, and soil is at least 1.5 m deep to ensure sufficient water holding capacity. Earth basins have proven successful, especially for growing fruit crops where seedlings are usually planted in or on the side of the infiltration pit. In the northern province of Tigray, Ethiopia, micro-basins about 1 m long and 0.5 m deep are often constructed along retention ditches for tree planting. Sweet potato ridges/bunds in southern Uganda fall into this category. In the Kwale district of Kenya, tied ridges and small basins have been reported to improve maize yields by more than 70%. In the Axum area, in northern Tigray, these retention ditches both prevent large volumes of surface runoff from flowing down steep escarpments, and have revived natural springs that, according to local communities, had dried out probably due to severe upstream deforestation. The technique is widely practiced in the Taveta Division of Taita-Taveta District and Baringo District in Kenya. The main crops grown using this technique include maize, beans and pigeon peas.

Excavated bunded basins (majaluba)

Excavated bunded basins (majaluba in Kiswahili) are widely used in Mwanza, Shinyanga, Tabora, Singida and Dodoma in Tanzania, and have become the most important source of paddy rice in the country. Majaluba are 0.2–0.5 m deep and are surrounded by bunds of scooped soil on the field perimeters (Fig. 27). Normally, the bunds are 0.3–0.7 m high. Farmers usually begin by constructing small majaluba, for example, 10 m × 10 m, and then progress to large majaluba of about 1 ha. This system is one of the methods of runoff utilization, management and storage for the production of paddy rice. It is estimated that 32% of Tanzania's rice production is grown on cropland where this rainwater harvesting technology is practiced.

Figure 27: *Excavated bench terraces*

Flood diversion and water spreading (spate irrigation)

Spate irrigation diverts and distributes surface runoff from macro-catchments flowing into seasonal watercourses—gullies and ephemeral streams/water courses—onto cropland through a network of canals/ditches or by flooding. The water is retained by ridges/ short bunds to spread the flow without causing erosion. Spate irrigation is similar to inundation because it involves construction of structures to retain floodwater. However, it differs from inundation in that, in addition to the barrage or weir to divert floodwater, it also includes channelling water through conveyance systems. These may be simple open furrows or lined canals. Thus, flood diversion is a system of irrigation, but on a seasonal basis. The technology is used in Baringo and Turkana Districts, on alluvial and colluvial soil fans at the base of ridges, escarpments or piedmont plains, for the production of grain crops, including sorghum. Sorghum and millet are also planted on the banks of seasonal streams and natural depressions in these areas. Similar techniques are used to grow maize and sorghum in Tanzania.

Spate irrigation in northern Ethiopia and Eritrea involves capturing and diverting storm floods from hilly terrain into levelled basins in the arid lowland croplands. In Kobo Wereda (south of Tigray), spate irrigation systems are well developed, with main diversion canals, secondary/branch canals, tertiary canals and farm ditches that distribute flood water into cultivation basins surrounded by contour bunds to enhance uniform water application. A series of main canals, each serving a different group of farmers, reduces floods. Farmers in the arid Kobo plains of northern Ethiopia have developed a traditional irrigation system that diverts part of such floods to their farms and sustains livelihoods that would otherwise be impossible. These systems are similar to those developed by the early settlers of the Negev Desert in Israel. They have also been tried in Konso, southern Ethiopia.

In western Sudan, terraces and dykes are used to spread runoff from wadis onto vertisols. The potential of these systems is enormous and, if improved and promoted, could help improve food security. Using external catchments to collect runoff immediately adds water to the field scale water balance.

Spate irrigation manages rainfall that occurs in high intensity storms. Such storms—normally occurring only within short rainy seasons—generate massive amounts of runoff that would normally disappear quickly down ephemeral watercourses and be lost.

Inundation

Inundation is the practice of collecting runoff behind a bund where it stands until the planting date for the crop approaches. The land is then drained, and the crop is sown and grows to maturity using the water stored in the soil. This technique also includes naturally occurring short-term flooding in plains and valleys. Sophisticated systems may include series of bunds with sluice gates and spillways to create several flood areas. The technique works best on deep soils with a high water holding capacity that retains adequate water after flooding. The selection of suitable crop cultivars is also important as the soils may be poorly aerated early in the growing period. The technique was introduced in Kenya's Turkana District in 1951.

Harvesting runoff from roads, footpaths and compounds

In many parts of East Africa, farmers have developed simple techniques (e.g. Fig. 29) to direct sheet and rill runoff from roads, footpaths and household compounds either onto crop land or into storage structures, such as ponds. These techniques can be used for either (i) blue water or (ii) green water harvesting. The compacted crusts of footpaths, dirt roads and compounds produce high volumes of runoff. These techniques are used to harvest runoff upstream for productive purposes downstream.

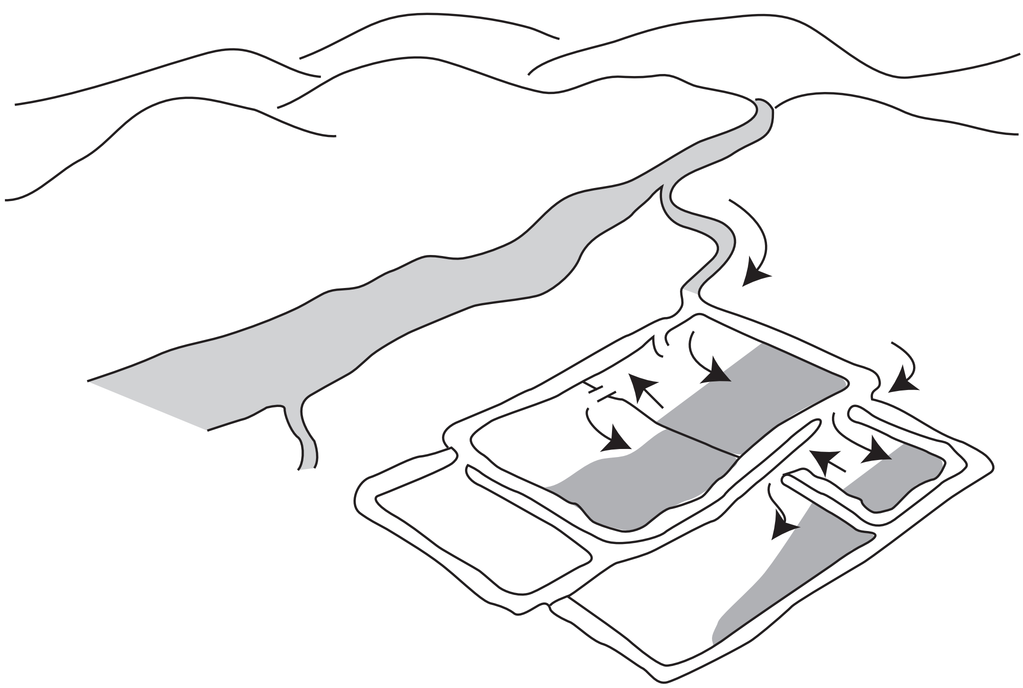

Figure 28: *Excavated basins to harvest road runoff*

Systems that harvest road runoff range from simple diversion structures that direct surface water into crop fields, to deep trenches with check dams that allow both flood and subsurface irrigation. Where surface conditions permit, storage in pans can be quite cost-effective, as has been demonstrated by farmers in Lare, Nakuru District, Kenya. In one project, over 1,000 pans were dug to trap road runoff and the area was transformed from a food-aid recipient to a net exporter of food.

In Tanzania, tapping road runoff for supplemental irrigation is widely practiced. Farmers divert runoff straight into fields or infiltration pits. Farmers planting rice along the main highway have greatly benefited. Their crop yields have improved and they have been able to diversify the crops they grow because harvesting road runoff has increased soil moisture and supplemented direct rainfall.

At Adigudum in Tigray, Ethiopia, farmers made improvements to a borrow site (see below) to make it into a dam. The dam stores water for livestock and reduces the distance they have to walk to water, especially during the dry season. One case study describes a method of harvesting road runoff developed by farmer Musyoka Muindi of Mwingi District, Kenya, that has become a standard technique quoted in text books. The system comprises an excavated main channel about 300 m long, which diverts road runoff from the road to the farm. Once on the farm, the runoff is led into a channel—rather like a diversion ditch—dug across the predominant slope. At the end of a channel, popularly known as *fanya chini*, the water is diverted around a bend into another similar channel where the flow is in the opposite direction. This is repeated, forming a zigzag reticulated system (Fig. 30). At certain points and in specific channels, water control gates determine the direction of flow. The channel dimensions are about 1 m deep, and 1–2 m wide. The earth embankments of the channels are stabilized with grass or sugarcane (Mutunga *et al.,* 2001), and are 1.5 m high, and spaced 18 m apart—somewhat larger than average. The vertical intervals between structures on the slope are thus about 0.9 m.

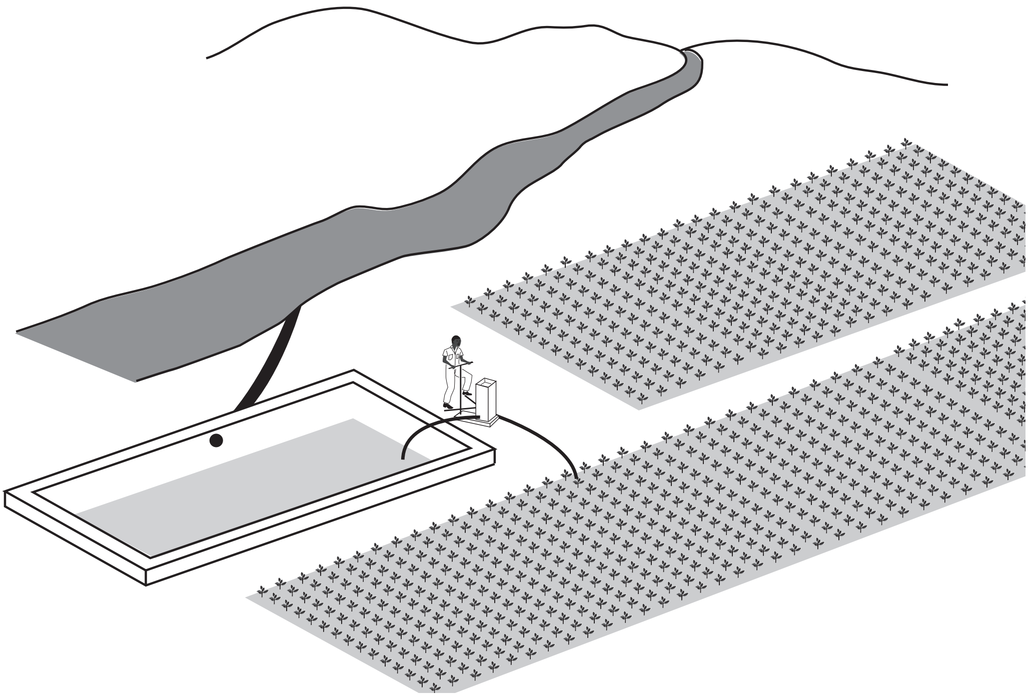

Figure 29: *Harvesting road runoff into channels for crop production*

Runoff from railway lines and borrow pits

Although railway lines are few and far between, they are used for water harvesting in many parts of Tanzania. Because they are paved and are usually raised above adjacent land, water runs off by gravity flow. In semiarid Singida, Tanzania, farmers collect runoff from railway culverts to irrigate 150 ha of their smallholdings (SIWI, 2001). In other areas, farmers use roadside pits (created when '*murram*' is dug out for road construction) as an important source of domestic and agricultural water. The scope for linking infrastructural development, water provision and, indeed, rainfed agriculture, is greatly underestimated.

Earthen bunds

Earthen bunds are structures constructed to pond runoff water. The most common are within-field runoff harvesting systems. These are becoming increasingly popular among smallholder farmers in East Africa, perhaps because here farm units are small and farmers sometimes have no opportunity to tap external catchments. Within-field systems also tend to require less mechanization, relying more on manual labour and draught animals. In design, earthen bunds follow the contours, and have spillways at 20 m intervals to control the application of surface water to each crop section. Bunds are constructed at 15–20 m intervals and the catchment-to-cultivated-area ratio ranges from 5:1 to 20:1 (Pacey and Cullis, 1986). There should be a deliberate effort to distinguish between bunds meant for within-field water harvesting and those meant for conventional soil and water conservation (Fig. 30). In the runoff harvesting system, a 'catchment' is maintained within the terrace to provide runoff that will add to the natural rainfall, while under conventional bunding, the whole terrace is cultivated.

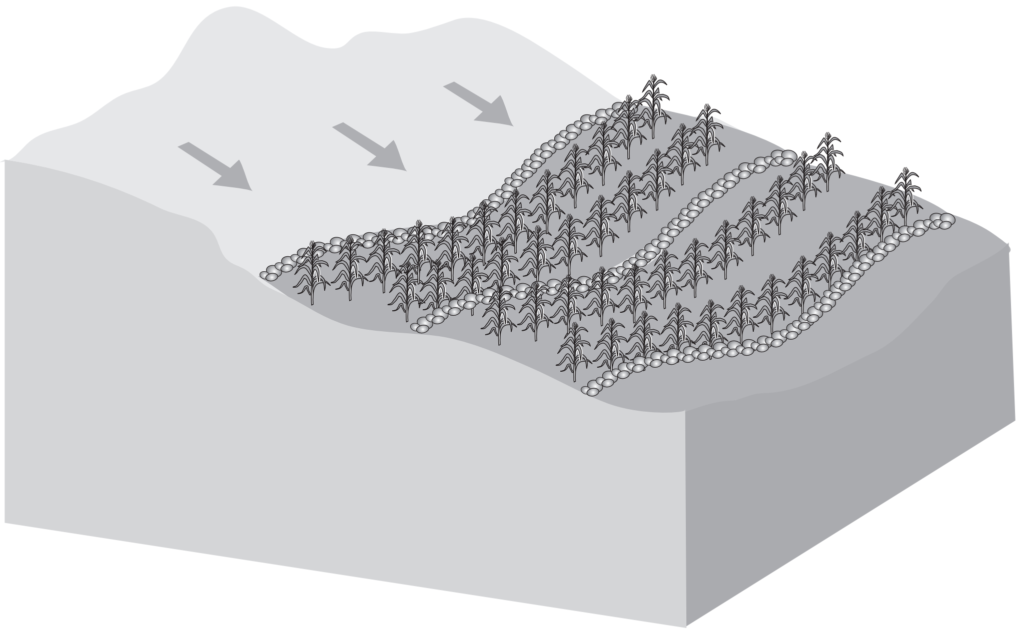

Figure 30 : *Contour bunds for field crops*

Contour bunds

Contour bunds are small earth or stone/trash line embankments constructed along a contour. The embankments trap and retain water flowing down the slope. The area behind the bunds can be levelled to ensure even infiltration. The interval between contour bunds varies, depending on the slope and soil type. Contour bunds can be constructed manually or mechanically. Attempts to promote the technique have been undertaken in Isiolo and Laikipia Districts in Kenya, mainly by NGOs, as well as in dry areas of southern Kenya. Adoption of contour bunds in northwestern Somalia has reportedly increased yields of sorghum by up to 80%.

Semi-circular bunds (hoops)

Semi-circular bunds (also known as 'demi-lunes' or crescent-shaped bunds) are earth embankments in the shape of a half circle with the tips facing upslope (Critchley and Siegert, 1991) (Fig. 31). Water is collected from the area above. The depth of water is determined by the height of the bund and the position of the tips. Excess runoff discharges through the space between the tips of adjacent bunds. The bunds are staggered, so that excess runoff from one row is intercepted by the row below it. The size of the cultivated area enclosed by the bunds depends on the amount of rainfall.

In the Busia District of Kenya, semi-circular bunds are made by digging out holes along the contours. The size of the holes and the spacing of the bunds are dictated by the type of crop or farming system. For fruit trees, the holes are at least 0.6 m in radius and 0.6 m deep. The subsoil excavated is used to construct a semi-circular bund, with a radius of 3–6 m, on the lower side of the pit. The bund height is normally 0.25 m. The planting pits are filled with a mixture of organic manure and topsoil, which provides nutrients and also helps retain moisture. Farmers often plant seasonal crops, such as beans, other vegetables and herbaceous crops, in the pits before the tree crop develops a shade canopy. Semi-circular bunds are common in the semiarid areas of Kenya (Turkana and Baringo Districts), Ethiopia and Tanzania, where annual rainfall ranges from 200 to 275 mm, and land slopes are less than 2%. In these areas, farmers have constructed semi-circular bunds for rangeland rehabilitation, annual crops, reseeding grassland, and for fodder, shrubs and trees. Semi-circular bunds have also been adopted to establish tree seedlings in denuded hilly areas in southern Uganda.

Larger semi-circular bunds are suitable for rangeland rehabilitation and fodder production. For trees, the runoff water is collected in an infiltration pit at the lowest point of the semi-circular bund, where the seedlings are planted. The main problems associated with this type of bund are:

- they are difficult to construct with animal draft; and
- they require regular maintenance.

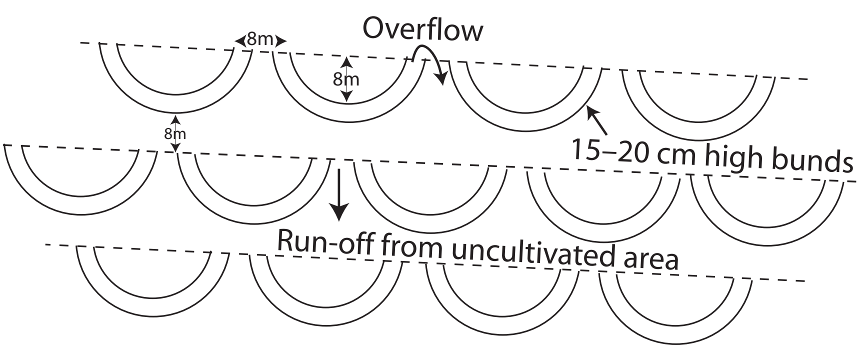

Figure 31 : *Layout of semi-circular bunds*

Circular bunds

Circular bunds are circular depressions (3–4 m in diameter and less than 1 m deep) constructed by excavating a pit and using the excavated soil to construct a perimeter bund that prevents runoff in any direction. A variety of crops are intercropped within the bund. Circular bunds are common in southern Ethiopia for banana cultivation.

Trapezoidal bunds

Trapezoidal bunds are large earth embankments, sometimes over 100 m long, trapezoidal in shape, with wing walls at about 135° facing upslope. The bunds are usually spaced about 20 m apart, and are arranged so that excess runoff from one bund can find its way to the next. The tips of the embankments are placed on the contour line and the base along the lowest contour. The top of the embankment is level and higher than the ground level at the tips. Water flowing down slope is trapped and retained behind the bund up to the level of the tips. Any excess overflows around the tips into other bunds in the system, or into natural drainage courses. The size depends on the slope and but may be from 0.1 to 1 ha. The width of the base of the embankment ranges from 2.6 to 5.8 m.

Trapezoidal bunds are traditional in several arid and dry semiarid environments in the Horn of Africa (Kenya, Somalia and Sudan). They are generally constructed by hand for subsistence cultivation of crops such as sorghum and millet. An example is '*teras*', a system of large earth bunds with straight walls, used to cultivate drought-tolerant crops, in areas where annual rainfall is only 150-300 mm. Trapezoidal bunds collect runoff from beyond the immediate cropped area.

Large trapezoidal bunds (120 m between upstream wings and 40 m at the base) have been tried in arid areas of Turkana District, northern Kenya, for sorghum, trees and grass.

Tied ridges

The purpose of tied ridges (Fig. 32) is to increase surface storage and allow more time for rainfall to infiltrate the soil. Closely spaced ridges run along the contour and are tied by smaller ridges—cross ties—at right angles that divide the ground into rectangular depressions. The cross ties are usually lower than the ridges so that, when the depressions fill and overflow, runoff will flow along each ridge and not down the slope. Marker ridges are pegged along a contour at intervals depending on the slope. Planting ridges are then made following the marker ridges. Marker ridges are planted with Vetiver grass to help trap the water and reduce runoff. Across the planting ridges, box ridges are made to retain water along the furrows of the planting ridges. The height of the box ridges is lower than that of the planting ridges to prevent accumulation of water that may damage the planting ridges. Tied ridges are also constructed at the end of planting ridges to prevent excess water from moving out of the field.

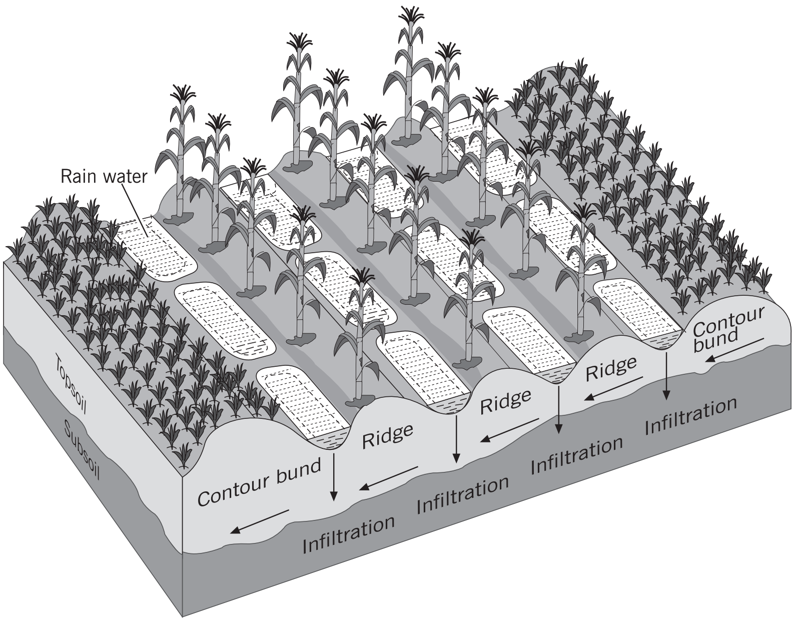

Figure 32: *Ridging or listing*

Broadbed and furrow systems

Broadbed and furrow systems are a modification of contour ridges, where a deliberate effort is made to ensure that there is a 'catchment' ahead of the furrow, and that there is a within-field micro-catchment water harvesting system. Furrows may be used as an in situ means of storing harvested rainwater. They are made before or after planting to store water for future use by the plants. A variation on the use of topographic depressions, furrows store water between the rows of crops. Mud dams or barriers may be constructed every 2–3 m to retain water for longer periods of time, and avoid excessive surface runoff and erosion. Raised beds spaced 1 m apart and uncultivated ground between rows also help trap rainwater in the furrows (Figs. 33 and 34).

In Ethiopia, Kenya and Tanzania, the broadbed furrow systems are made as small earthen banks with furrows on the higher side, which collect runoff from the catchment area between the ridges. Catchment areas are cleared of vegetation and left uncultivated to maximize runoff. Crops are planted on the sides of furrows and on the ridges. Plants that need a lot of water, such as beans and peas, are usually planted on the higher side of furrows, and cereal crops, such as maize and millet, are usually planted on the ridges. The distance between ridges is 1–2 m depending on the slope, the size of the catchment area and the amount of rainfall.

Contour furrows are suitable for areas where the annual rainfall is 350–700 mm, slopes are 0.5-3% and soils are fairly light. On heavier, more clayey soil they are less effective because the infiltration rate is lower. Although contour furrows increase crop yields in drier areas, the labour requirements are higher than for conventional farming, and the intricacies involved in construction deter many farmers from adopting them.

Contour furrows in the Baringo District of Kenya are small earthen ridges, 0.15–0.2 m in height, spaced approximately 1.5 m apart on the contour. Furrows, which are upslope, accommodate runoff from uncultivated catchment strips between the ridges. Small earthen ties within the furrow at a spacing of 4–5 m prevent lateral flow. The aim here was to concentrate local runoff and store it in the soil profile close to the plant roots. These contour ridges were designed for small-scale production of food crops. Cereals intercropped with pulses were recommended for this system. As this is a micro-catchment, or within-field catchment system, runoff from an external source is not required and may even damage the structures. To prevent overflow within the system, a cutoff drain is provided where necessary. Contour ridges may be used on a range of slopes, although their dimensions may need to be increased as the gradient increases.

The Guimares Duque method was developed in Brazil during the 1950s, and uses furrows and raised planting beds, on which cross cuts to retain water are made using a reversible disk plough with at least three disks. The furrows are usually placed at the edge of the cultivation zone (Fig. 35).

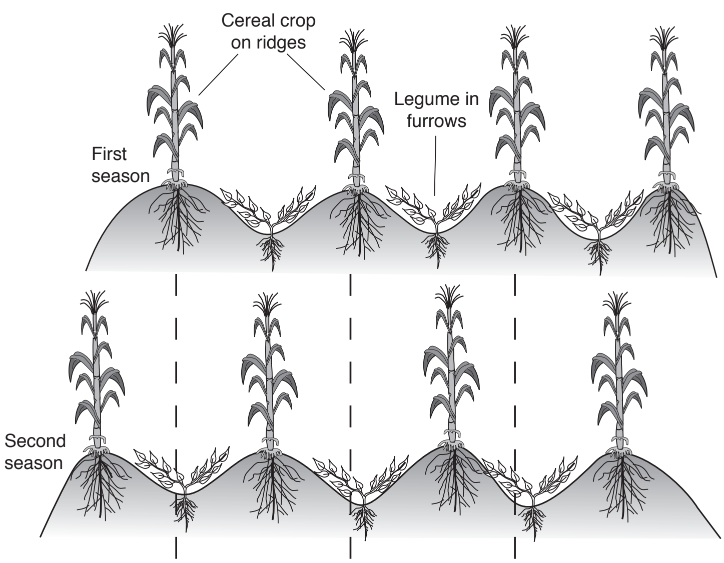

Figure 33: *Broadbed and furrow system*

Negarims

Negarims are small V-shaped embankments with the apex at the lowest point. Water is collected from the area within the V and stored in the soil profile at the apex. This technique is best for trees and shrubs. Catchment areas range from 16 m^2 in agroecological zone (AEZ) V to 1,000 m^2 in AEZ VII. Embankments are 15-20 cm high and, at the apex, basins are 40 cm deep. This technique has very little conveyance losses as water is used close to the source. The structures are also cheap to construct.

Negarims, or micro-catchment basins, originated in the Negev Desert of Israel. They are used to establish fruit trees in arid and semiarid regions where the seasonal rainfall may be as low as 150 mm. In design, they are regular square earth bunds, placed at 45° to the contour, to concentrate surface runoff at the lowest corners (Critchley and Siegert, 1991); they are, therefore, efficient in land utilization. *Negarims* are common in the Kitui, Thika and Meru Districts of Kenya for fruit tree production (Hai, 1998). The *negarim* technique is also used to establish trees and grow sorghum in the Turkana District.

Pitting techniques

Shallow planting holes (<25 cm deep) to concentrate surface runoff and build up soil fertility are found in many farming systems throughout Sub-Saharan Africa. They have many names and include *zai* pits (Burkina Faso), *matengo* pits (southern highlands of Tanzania), *tumbukiza* (for napier grass), and banana or pawpaw pits (Kenya). Moisture retention terraces and ditches are other micro-catchment techniques promoted and adopted in semiarid Sub-Saharan Africa. Pitting (digging holes of various sizes for growing crops) has been practiced as a method of water harvesting and conservation for both micro-catchment and external catchment systems. In East Africa, farmers have always grown crops such as bananas, coffee, tea and many types of fruit tree in pits. However, they still consider pits for field crops such as maize, millet and beans as a novel technique.

Infiltration pits/retention ditches

Infiltration pits located at strategic points control floods; seepage from the pits also provides water for various crops planted close to them. The pits also collect runoff from hillsides, roads and footpaths. Such infiltration trenches/ditches are dug along the contour—at specified intervals according to the slope—for retaining runoff in banana plantations in the Mbarara and Rakai Districts of southwestern Uganda.

Zai pits

Zai pits—also simply referred to as planting pits—are an indigenous method of water harvesting in Burkina Faso and have recently been introduced into Kenya. The pits are small: about 30 cm in diameter and 15–20 cm deep. During excavation, the soil is thrown down slope to form a small embankment. To improve fertility, farmers place manure or compost in the bottom of the pit before planting four to eight seeds of a cereal, for example, maize (Fig. 34). The *zai* system was introduced from the Sahel Region of West Africa (crop Critchley and Siegert 1991), where it has been practiced for centuries. In Kenya, experiments with *zai* pits have shown good results. *Zai* pits are effective because the one technique harvests water, conserves moisture and improves fertility. In Kenya the *zai* system has been somewhat modified. The Kenyan Agricultural Research Institute (KARI) has adapted the manual pitting system, the *katumani* pit which is similar to the small *zai* pit, to local conditions at Katumani, in the Machakos District. In the Njombe District of southern Tanzania the pits are bigger and deeper (at least 0.6 m deep) and 20 litres of manure are added. Since the annual rainfall is nearly 1,000 mm, the farmers plant about 15-20 seeds of maize per pit and the yield per pit is more than double those on conventional tilled land.

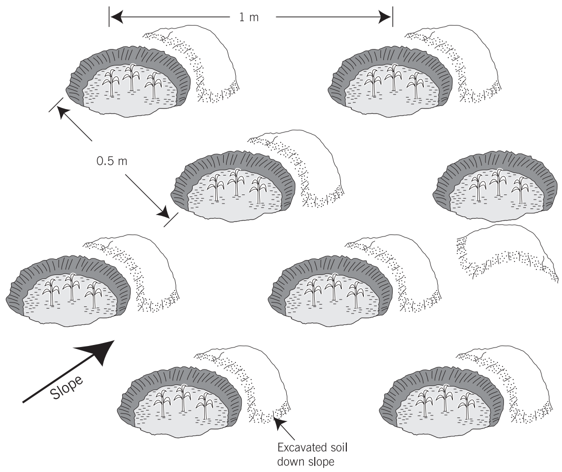

Figure 34: *Zai pits for water harvesting and conservation*

Chololo pits

Chololo pits are named after the Tanzanian village where they were invented by Kenneth Sangula of Dodoma Region. Kenneth said that he discovered this pitting method, a modification of the *zai* pits of the Sahel, almost by accident. *Chololo* pits comprise a series of pits running along the contour, about 22 cm in diameter and 30 cm deep, in rows 60 cm apart with 90 cm between rows. The soil removed during excavation is heaped into a small bund around the hole. Ashes (to expel termites), farmyard manure and crop residues are added, then covered with soil while retaining sufficient space in the hole for runoff to pond. The organic materials hold water and retain moisture. One or two seeds of either maize/millet or sorghum are planted per hole. Crops usually survive even during severe rainfall deficits, and yields have tripled. Because the smaller holes require relatively less labour, this method has been adopted by many farmers, and is easily transferable (Lameck, personal communication).

T-basins

Another technique practiced in Kenya which draws from external catchments is known locally as T-basins because the basins are interconnected in a T-shape External catchments, such as footpaths and roads, convey runoff to the T-basins through a system of narrow channels. The water collected in this manner is retained in the T-basins, where it infiltrates into the root zone of surrounding crops. Unlike circular root-zone basins, this system can be used for both tree and non-tree crops. Traditionally, the T-system is used by farmers in Nambale Division of western Kenya for growing bananas, mangoes, citrus and passion fruit. This method is used also in Mwingi (Mburu, personal communication).

V-basins

Tree crops have long been grown in basins and pits. In the Turkana Region of Kenya, Critchley *et al.* (1992) described V-shape pits with arms extending upslope for 10 m and tips on the contour. These pits had a capacity of about 2.5 m^3. The spacing between the individual micro-catchment of each pit was not precise; the catchment area could reach up to 150 m^2 in the driest areas. In more favourable zones with more rainfall, individual catchments were smaller, around 25 m^2 and their capacity was lower, 1.2 m^3. Tree seedlings are planted behind each pit immediately after the beginning of the rains.

Root zone basins

Root zone basins are circular pits that are deeper than average so as to store enough water to provide adequate soil moisture without the danger of breaching basin walls (Bittar, 2001). They are usually 0.6–1.2 m in diameter, and the bunds are 0.1–0.3 m high. Basins are tilled to a depth of 0.6 m to improve the capacity of the root zone to store harvested water. Moisture retention in the root zone is enhanced by adding manure and by mulching with vegetative matter. Runoff is channelled, by means of slight bumps about 0.05 m high built across predominantly external catchments (paths, roads and compounds), into collecting channels, and from there into the root zone basins.

Five by nine pits

'Five by nine' pits are 0.6 m^2 by 0.6 m deep planting pits for maize. They are similar to *zai* pits but are larger, and square rather than round. The name 'five by nine' refers to the five or nine maize seeds that are planted on the pit diagonals (five for dry areas and nine for wet areas). This type of pit holds more manure than a *zai* pit; hence, yields are higher and more sustainable. The Kenya Institute of Organic Farming has popularized this system, especially in the Kirinyaga, Mbeere, Murang'a and Machakos Districts of Kenya. Here, the pits have helped farmers maximize production on their farms. The pits can also be re-used for up to 2 years.

Tumbukiza pits

Tumbukiza pits have revolutionized fodder production and improved soil fertility. *Tumbukiza* in the Kiswahili language means 'throw all in'. Huge pits, 0.6-0.9 m in diameter and 0.6-0.9 m in depth are filled with trash, vegetative matter, farmyard manure and topsoil, then fodder crops, preferably napier grass, are usually grown. In the Nyando District of Kenya, farmers apply one 20-litre jerrycan of water per hole per day during the dry season. The organic material in the pits retains the water, enabling the napier grass to grow rapidly and yield one cut per hole per month. Thus, if a farmer owns one cow, he/she needs 30 pits; these, when watered at a rate of one jerrycan a day, will provide enough fodder for the cow for the month. At the end of one cutting cycle (30 days), the fodder has grown enough to allow the next round of cutting . This method has been so popular that farmers all over the country have been adopting it. However, excavating the pits is labour intensive and discourages adoption among the poor.

Utilization of riverbeds and high water tables

In the arid and semiarid lands throughout Africa, residual moisture in sand rivers and seepage from streams has traditionally been used to grow crops. Generally, women grew crops, such as arrowroot, sweet potatoes, fruits and vegetables, in the valley bottoms to ensure that their families were well nourished. Sugarcane and rice are also traditional crops in river valleys. These valley bottoms are very important in providing food security in semiarid areas prone to regular droughts. An analysis of farmer innovators in the Mwingi District of Kenya showed that approximately half of all innovations in soil and water management were to be found along dry riverbeds (there being no permanent rivers in the district). In addition, the farmers consider water table management to be easy and, therefore, adoption of related innovations has been good (Mburu, 2000).

Innovative methods of utilizing riverbeds and high water tables were also found among farmer innovators in Kenya and Tanzania. For instance, in the Mwingi District of Kenya, the conventional way of planting sugarcane is simply to drill a cutting into the riverbed. However, one farmer, Mrs. Lucia Kakundi Kitengu, developed an innovative method of planting sugarcane in pits (Fig. 35). Through experimentation, she found the optimum design for her farm, which borders a sand river. She dug 1 m^2 holes, 0.6–0.75 m deep, spaced about 0.6 m apart within rows (edge to edge), and 0.6 m between rows. She varies the depth of the holes according to distance from the stream bank, deepening the holes that are further from the river. She then plants four sugarcane cuttings in each corner of each pit, and applies manure. During the rainy season, the holes get flooded, replenishing not only water but also nutrients. As a result, the sugarcane grows more quickly, survives droughts better, yields much larger and healthier cane, and so fetches prices more than triple those fetched by sugar cane grown conventionally on flat ground without the benefit of pits. This innovation has been copied rapidly by other farmers.

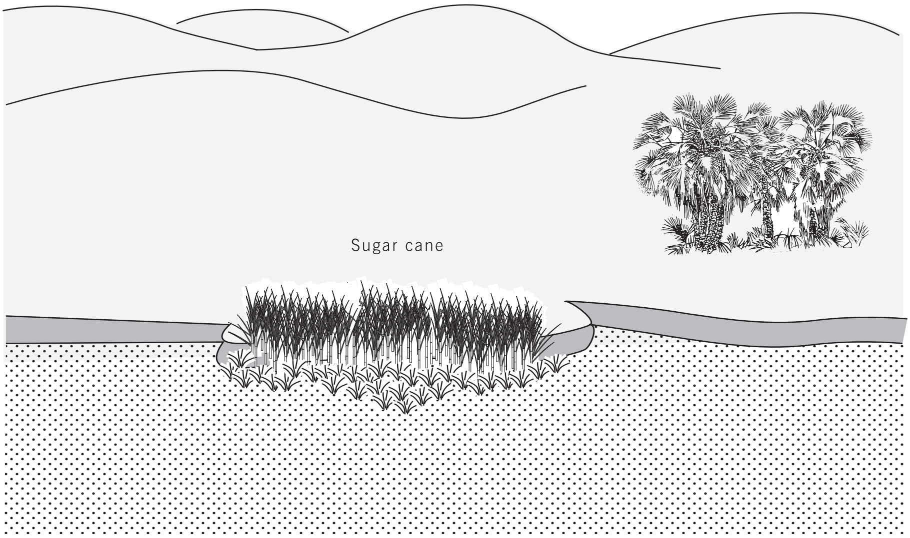

Figure 35: *Utilizing high water tables in riverbeds for sugarcane production*

In the Dodoma region of Tanzania, farmers take advantage of residual moisture in sand riverbeds after the rains subside (Lameck, personal communication). They make ridges in the sand and plant sweet potatoes, which take about 3 months to produce tubers, by which time the dry season has started. In contrast, the use of valley bottoms in Kenya has been limited as the *Agriculture Act 318* forbids cultivation of riverbeds. This legislation is seen by many farmers as having a negative effect, because sand rivers are usually of little use during the dry season, and using them for crop production then would have little impact on soil erosion once the rainy season resumed.

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Chapter 5

Conservation tillage

5.1 Introduction

Conservation tillage is defined as any tillage practice designed to minimize the loss of soil and water, and which leaves at least 30% mulch or crop residue on the surface throughout the year (Rockström, 2003). However, with respect to small-scale farmers in semi arid Sub-Saharan Africa, conservation tillage is defined as any tillage system that conserves water and soil while saving labour and traction. Conservation tillage aims to reverse the trend towards lower infiltration in farming systems due to compaction, formation of soil crusts and lower water holding capacity due to oxidation of organic materials (due to excessive cultivation of the soil). From this perspective, conservation tillage qualifies as a form of water harvesting, as it impedes runoff and stores soil water in the crop root zone. Unlike conventional tillage systems based on soil inversion to help water infiltrate the soil and allow roots to penetrat e easily, conservation tillage covers a spectrum of non-inversion practices—from zero-tillage to reduced tillage—which aim to maximize soil infiltration and productivity by minimizing water losses (evaporation and surface runoff) while conserving energy and labour. Conservation tillage can be practiced on most farmland, whereas techniques such as harvesting and storing rainwater for supplemental irrigation can only be practiced in certain areas.

Promoting animal-drawn conservation tillage tools, such as rippers, ridgers and sub-soilers, among smallholder farmers in the semiarid Machakos and Laikipia Districts (Kenya) has resulted in significant improvements in water productivity and crop yields. There are many documented examples of successful conservation tillage practices that have improved crop yields by conserving soil water and nutrients and/or reducing draught power needs (Rockström *et al.,* 1999). Case studies in the Laikipia and Machakos Districts of Kenya show that conservation tillage (sub-soiling and ridging) have improved yields by more than 50%. The potential of conservation tillage is tremendous, especially because communities already use animal-drawn implements to till the land and because conservation tillage implements are compatible with their conventional tools. In large-scale farming systems in the Laikipia District, tractor-drawn conservation tillage implements have improved wheat yields. Pastoral communities are also not being left behind. In the Laikipia District, scratching the ground with animal- or tractor-drawn tools has improved pastures.

In Dodoma, Tanzania, trench cultivation, a form of conservation tillage, has been developed by innovative farmers. Here, shallow trenches are dug, filled with organic material, and covered with soil to form ridges on which crops are planted. Putting organic material under the ridges improves soil fertility and water holding capacity and seems to be an improvement of the furrow and ridge systems used in Kitui and Machakos. The furrows and ridges are made using animal-drawn mould board ploughs. Seeds are planted in the furrows, which collect water between the ridges. After seedlings develop, weeding (using animal drawn ridgers) ensures that the furrows and ridges alternate—the crops grow on the ridges while the furrows capture and concentrate the rainwater. In such trench cultivation, the ridges and furrows are rotated after each growing season and have enhanced crop yields in otherwise low yielding areas.

5.2 Benefits

Unlike conservation tillage, conventional tillage has been found to destroy the structure of the soil and cause compaction. This has negative effects on soil aeration, root development and water infiltration, among other things. More important, but less noticeable, is the destruction of communities of soil microbes by disturbing and turning over the soil, which is then exposed to drastic atmospheric and climatic conditions (Kaumbutho, 2000). Conservation tillage, therefore, takes care of this by applying four main principles:

- Zero or minimum soil turning,
- Permanent soil cover,
- Stubble mulch tillage, and
- Crop selection and rotations.

An important aspect of conservation tillage practice involves ripping the land with tined implements or sub-soiling the land immediately after crops are harvested, to break the plough pans. Suitable equipment includes animal-drawn sub-soilers, rippers, 'ridgers', planters, and weeders (Biamah *et al.*, 2000; Elwell *et al.*, 2000).

Conservation tillage has been very successful in harnessing rainwater and improving yields . Field visits in the Machakos District (Kenya) revealed that below-average short rains (2001/2002), farms where conservation tillage was practiced had good harvests while neighbouring farms without convention tillage had literally no harvest—a conspicuous contrast. Conservation tillage has several attractive effects on water productivity (Rockström *et al.*, 2001) compared with traditional soil and water conservation systems such as *fanya juu* terracing in Machakos District. In addition to enhancing infiltration and moisture conservation, it enables improved timing of tillage operations, which is crucial in semiarid rainfed farming.

Minimum tillage

In its extreme form, minimum tillage includes zero tillage, and/or no-till subsystems where the land is planted by direct seed drilling without opening any furrows or pits. Old crop residues act as a mulch and weeds are controlled using herbicides. In the dry areas of East Africa, zero tillage has not worked well due to poor infiltration (as soils are easily self-sealing) and the prohibitive cost of herbicides. In Kenya, 'no-till systems' used to be used mostly in large-scale mechanized wheat/barley systems, but smallholder farmers have recently started experimenting with this system with good results, as in Machakos, Laikipia and Nyando districts.

Minimum tillage also takes the form of 'spot tillage '. In this case, special tools or augers are used to make small pits just for one or two seeds of grain over the old crop residues; weeds are controlled using herbicides. In Arumeru District, in the Arusha Region of Tanzania, the digging of small planting pits with hand-hoes has been quite efficient in concentrating surface water and plant nutrients as well as breaking hard plough pans. The technique is labour-intensive, but simple and is an efficient way of assuring a crop's survival even when rainfall is inadequate and resources such as fertilizers and manure are unavailable.

Strip tillage involves cultivating the land in strips at the position of the crop rows, leaving the rest of the land untilled, to generate runoff and reduce labour. It has successfully been practiced in Tanzania (Elwell *et al.*, 2000). Where access to equipment is possible, the operation can be advanced to simultaneously insert seeds (and even fertilizer) into the soil while breaking the hard pan in the same single pass. Minimum tillage by ploughing with a 'magoye ripper', which is adapted from Zambia, has become popular among smallholder farmers in Kenya and Tanzania (Biamah *et al.*, 2000; Lundgren and Taylor, 1993). The subsoiler digs 25-30 cm into the soil breaking the plough hard pan. It can also be used to make furrows about 80 cm apart. In Arusha Region, Tanzania, where annual rainfall ranges from 400 mm to 1,200 mm, the magoye ripper was found to reduce labour and enhance crop yields in the dry years (IIRR, 1998).

Manual subsoilers have also been developed by innovative farmers (Thomas and Mati, 1999). The equipment comprises a long hoe that can cut into about 30 cm of soil, and which is made from old car springs; it is therefore quite durable and cost-effective. The subsoiler is used once every three years, to break soil crusts developed from prolonged use of the mould-board plough.

Stubble mulch tillage

Stubble mulch tillage has been used as a water conservation technique in Kenya, especially in the mechanized large-scale farms growing wheat and barley as found in Kitale and Time in Kenya (Mati , 1999). Normally, this involves chopping crop residues and spreading them on the surface or incorporating them during tillage with tined implements such as the chisel plough. Stubble mulch tillage reduces labour and farm-power requirements, and, as such, it is cost-effective. Increased yields have been reported, especially in marginal areas. The system results in an improved and stable soil structure, with reduced direct impact of raindrops on bare soil, thus minimizing soil erosion. The moisture retention capacity of the soil is also enhanced by the residues; hence, crop survival is better during dry spells or drought. In a study at Katumani Research Station in Machakos, Kenya, Okwach (2000) obtained results showing that mulch tillage effectively reduced runoff and soil loss compared with conventional tillage systems.

Ridging and tied ridges

Contour ridges (or contour furrows) involve making ridges along the contour at a spacing usually of some 1-2 m. In Kenya and Tanzania, ridging is normally done for crops such as potatoes, tobacco, groundnuts and even for maize (Assmo and Eriksson, 1999). Ridging for maize involves 'earthing' up the maize rows during the weeding process, albeit the maize is first planted on the flat. Plough planting is a commonly used practice in Tanzania's Arusha Region (Hatibu et al., 2000). Ridging systems are mostly suited for areas with an annual rainfall ranging from 350 to 750 mm (Critchley and Siegert, 1991. Among farmer innovators of East Africa, ridging has emerged as one innovation that has made a big difference in crop production (Thomas and Mati, 2000).

In the semiarid areas, tied ridges are made by modifying normal ridges. The technique involves digging major ridges that run across the predominant slope, and then creating smaller sub-ridges (or cross-ties) within the main furrows. The final effect is a series of small micro-basins that store rainwater in-situ, enhancing infiltration. Depending on the system, the crop is planted at the side of the main ridge, to be as close as possible to the harvested water while also avoiding waterlogging in case of prolonged rains. Tied ridges have been found to be very efficient in storing the rain water, which has resulted in substantial grain yield increases in some of the major dryland crops such as sorghum, maize, wheat, and mung beans in Ethiopia (Georgis and Takele, 2000). The average grain yield increase (under tied ridges) ranged from 50% to over 100% when compared with the traditional practice. This increase, however, will vary according to the soil type, slope, rainfall and the crops grown in dryland areas such as Kobbo, Nazreth, Meiso, Mekelle and Babilie in Ethiopia.

5.3 Linking conservation farming to rainwater harvesting

Introduction

It is without doubt that RWH is linked to conservation agriculture. However, the question that comes to mind is whether the two are independent, complimentary or dependent on one another. In other words is RWH a part of conservation farming or vice versa? Could one be a precursor to the other, where CA has to be employed before RWH or RWH before CA? Can CA do without ex-situ RWH? This paper attempts to show the relationship.

Conservation farming is an activity that contributes to in-situ RWH In order to understand the relationship between conservation farming and RWH, it is important to introduce the concept of the *Conservation farming unit (CFU)*. A conservation farming unit is an integral portion of a watershed that has characteristics of a RWH system, while at the same time conforming to the tenets of the hydrological cycle. It consists of a catchment platform, a combined conveyance and filtering mechanism, the storage, delivery (uptake by roots) and utilization components. The nature of technological interventions at this platform will determine the performance of the consequent processes

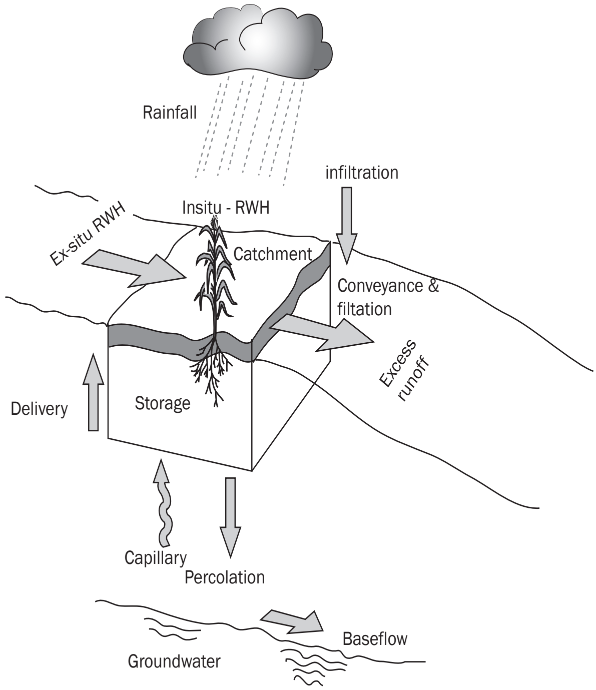


Figure 36: *Schematic drawing of CFU*

5.4 CFU's components and process

The catchment platform

This is the space within which all the conservation farming practices (such as no till, reduced till to biological measures) are carried out and represents the catchment component of the CFU. It starts from the surface of the farm and continues to the maximum depth attained by conservation farming implements such as rippers and tines. The nature of conservation farming will determine the efficiency of in-situ rainwater harvesting. There are three issues to consider here: Minimizing soil disturbance; Maximizing soil cover and Crop rotations or associations. Indeed, conservation agriculture refers to the simultaneous practice of all three.

Rainwater harvesting is thus an in-situ technique that conserves both soil and water. A combination of conservation tillage and terracing has thus higher benefits than either of these interventions done on their own. In the event that the water harvested is insufficient, it becomes imperative to seek ex-situ supplementation. Harvesting runoff water from external sources located in the upper catchments and channeling it via surface or sub-surface means to the farm contributes immensely on the supplemental water for irrigation. This is further explained below.

Conservation farming Practices

Minimizing soil disturbance aims at zero tillage and direct planting. Conservation tillage, which includes ripping, tied ridges, basins, strip tillage etc is a gateway to progressively achieve minimal soil disturbance. The benefits of these include improvement of soil structure and moisture storage. *Soil cover* is maximized through cover cropping, intercropping and the use of crop residues or mulch. It enhances moisture conservation, suppresses weeds, reduces erosion and soil temperature variation and also enhances soil fauna and microorganisms. *Crop rotations and associations* enhance nutrient replenishment and uptake; control of weeds, pests and diseases; integration of livestock, carbon sequestration and food security (RELMA, 2003).

Rainfall and irrigation

Crop water requirements can be met by sufficient and reliable rainfall, but this is not usually the case especially in Africa which most of its regions are semi arid and arid. Due to this supplementary irrigation is necessary. These sources provide water to the unsaturated root zone to meet crop and soil water requirements. In tropical agriculture, emphasis is given to the former but not all is captured,. this necessitates the creation of conducive conditions for insitu water collection

Increasing the effective rainfall is a means of making more efficient use of available water (Heun, 2001) by

- reducing runoff through leveling and terracing, water storage from RWH
- increasing infiltration through conservation tillage
- minimize deep percolation by improving soil texture and deep root zone
- plan cropping patterns that are consistent to rainfall patterns

Further, the amount of rain falling on the farmland will either be captured or lost depending on two factors; initially on the orientation of the CFU platform and later on the conservation farming technique. Forward sloping farmlands that are not terraced encourage runoff and soil erosion. However, forward sloping farmlands that are terraced impede runoff. On the other hand, level lands or benches and backward sloping terraces contain the water and encourage infiltration. Conservation farming aims at improving the management practices in order to boost the soil-water-environment for better crop performance.

Ex-situ rainwater harvesting

Ex-situ rainwater harvesting is a form of water provision for supplementary irrigation in the event that a CFU is unable to sustain the crop through its entire growing period. Ex-situ rainwater harvesting comes in the form of runoff catchment schemes. Here, runoff water that collects on the ground in homesteads, farms, paths and rural roads is channeled via mitre drains often into already existing trenches. These could take the forms of fanya juus or retention ditches or mere channels that lead the runoff water into silt traps.

Immediately after the silt traps, this water is conveyed through a PVC pipe with a mesh tied at the opening to trap vegetative material that may be washed into the underground tanks. The underground tanks could either be closed or open. Closed ones include sausage or spherical while the open ones are either ponds or plastic lined tanks. Water from these ponds is abstracted using simple rope and washer or treadle pumps for supplementary irrigation. Irrigation scheduling will depend on the conservation farming practice, soil moisture regime and crop characteristics during time of growth.

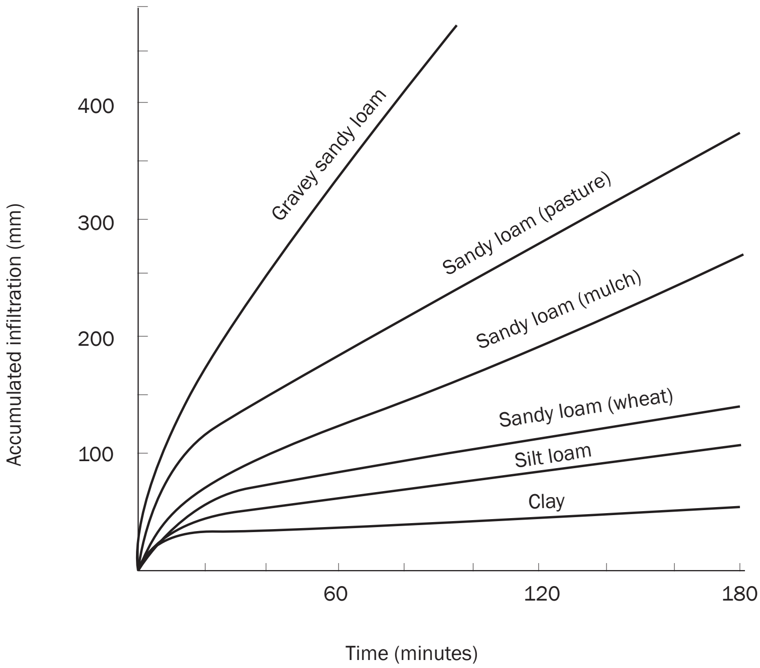
Examples of ex-site RWH techniques include:

- Runoff harvesting from hills, ground, homesteads, roads etc and storing this water in ponds, trenches, underground tanks, dams etc for supplementary irrigation.
- Pond
- Sausage tank
- Trenches with Bananas

Conveyance and filtration

The soil surface and profile represent the conveyance and filtration component of the CFU which occur simultaneously. The soil surface is a filter that determines the path rainwater will follow. Infiltration of water into the soil is controlled by gravity**,** capillary action, and soil porosity (Heun, 2001). Of these, porosity is the most important factor which is controlled by the conservation farming practices that influence soil structure and texture.

Rainwater entering the soil moves slowly into the underground whereas the water that does not infiltrate runs quickly over the ground. Depending on the soil type, as one of the major factors, it will determine the volume of runoff, its timing, and its peak rate of flow. The water that infiltrates determines the amount available for evapotranspiration and for deep percolation.



Source:Ministry of Agriculture and Forestry, New Zealand(2005)

Figure 37: *Typical infiltration curves for different soil textures.*

Water storage

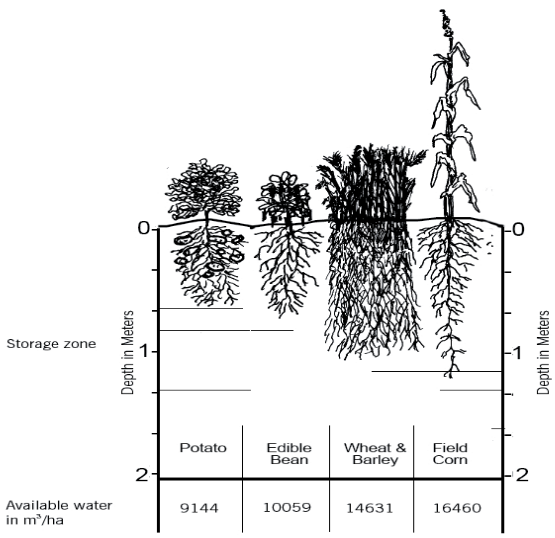
The root zone acts as a water reservoir and represents the storage component of the CFU. Water is held by capillary forces to the outer surfaces of the mineral particles of the soil. As water enters the soil, the pore spaces become filled. Eventually, excess gravitational water percolates through the macropores to the groundwater below, spring or surface water bodies such as rivers or lakes. The soil water regime is then said to be at field capacity. The remaining water held onto the soil particles is called capillary water. Under drought conditions, even the capillary water is removed until plants can no longer remain upright, and the soil water regime is said to have reached its wilting point. The amount of water between the field capacity and the wilting point is called the available water capacity

The deeper the rooting depth, the larger the reservoir. Silt and clay have undoubtedly the highest water holding capacities, as contrasted to sandy oriented soils. However, it is much easier for the crop to get capillary water during drought from loamy soils.

Table 3: *Water holding capacity (mm/cm depth of soil) of main texture groups. Figures are averages and vary with structure and organic matter differences.*

Texture	Field Capacity	Wilting point	Available water
Coarse sand	0.6	0.2	0.4
Fine sand	1.0	0.4	0.6
Loamy sand	1.4	0.6	0.8
Sandy loam	2.0	0.8	1.2
Light sandy clay loam	2.3	1.0	1.3
Loam	2.7	1.2	1.5
Sandy clay loam	2.8	1.3	1.5
Clay loam	3.2	1.4	1.8
Clay	4.0	2.5	1.5
Self-mulching clay	4.5	2.5	2.0

Source: Department of Agriculture Bulletin 462, 1960
Better soils(2005)



Ashley O.k. (2005)

Figure 38: *An example of available water (in m^3/ha) for different crops grown in a loam soil.*

Evapotranspiration

Evapotranspiration represents the delivery component of the CFU. Crop evapotranspiration (ET_C) is the amount of water a crop needs for growth. It is the start of all calculations for determining agricultural water demands. Evapotraspiration also represents the delivery component of the CFU.

$$ET_C = K_C.ET_O$$
$$ET_C = (K_{CB} + K_E).ET_O$$

Where K_C = Crop factor
K_{CB} = Basal Crop Coefficient
ET_O = Reference evapotranspiration
K_E = Soil Water Evaporation Coefficient
$(K_{CB} + K_E)$ = Dual Crop Coefficient

However, the actual evapotranspiration, $ET_{C\,ADJ}$ is given by;

$$ET_{C\,ADJ} = (K_S.K_{CB} + K_E).ET_O$$

Where K_S = Water stress coefficient

The Basal Crop Coefficient (K_{CB}) is derived by considering the growing stage, the ground condition, irrigation and conservation farming practices. The lower the ET_C, the lower the rate of withdrawal from the reservoir.

Yield production

Yield formation represents the utilization component of the CFU. Water is an essential commodity in dry matter production through photosynthesis. 80 to 90% of a plants cell protoplasm consists of water, still, during growth, plants use nearly all the water for transpiration. Transpiration is important in the attainment of crop yield. To attain maximum yield, maximum transpiration is needed. This is possible if good conservation farming practices are carried out throughout the growing period of the crop, with a view to conserving as much water as possible to attain high transpiration rates The relationship between transpiration and yield output is given in the formula below

$$Y_A = \frac{T_A}{T_M} Y_M$$

Where Y_A = Actual Yield
Y_M = Maximum Yield
T_A = Actual Transpiration
T_M = Maximum Transpiration

CFUs' hydrologic sufficiency in sustaining crop productivity

The question of whether a CFU is sufficiently independent to sustain crop growth depends on a number and combination of biophysical factors. These include: the rainfall regime; evaporation rates; infiltration capacities; water holding capacities as influenced by soil structure and texture; crop factors; soil surface conditions e.g. mulching, crop residue cover and vegetation cover. In the event that a CFU is unable to sustain a crop through its entire growing period, there is need for ex-situ rainwater supplementation. This is achievable through the harvesting and conveyance of runoff via mitre drains and silt traps, into the farm. Such water is either directly conveyed and spread into the farm or stored in underground sausage or cascades of spherical tanks prior to abstraction for supplementary irrigation (Oduor, 2003).

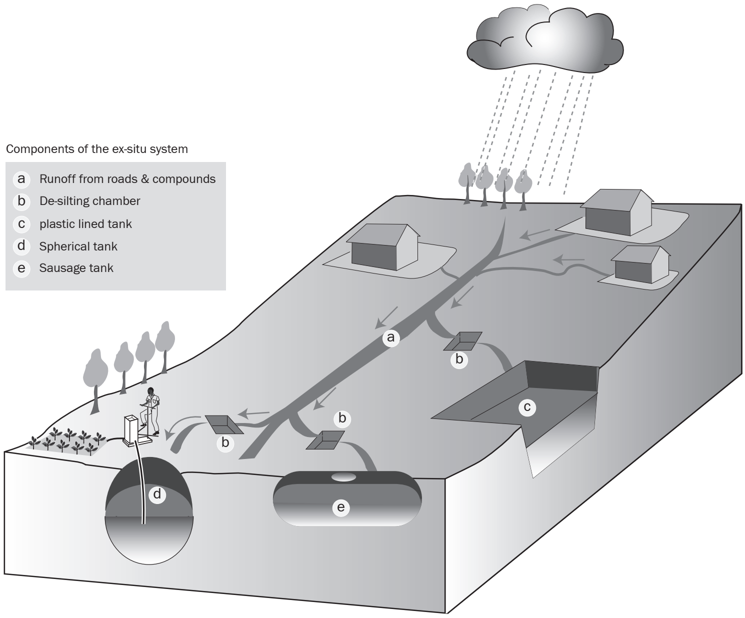


Figure 39: *Ex-situ rainwater harvesting System for supplementary irrigation*

Summary of operations of a CFU

Rainwater is captured in-situ and facilitated to infiltrate into the soil profile by various conservation farming practices. As it is conveyed by gravity through the soil profile, this water gets naturally filtered. The water is then consequently stored by the soil acting as a reservoir. The amount of water stored depends on the nature, type or a combination of conservation farming practices. Since the aim of conservation farming is to boost agricultural productivity, the readily available moisture held in the soil is delivered through osmosis to the crop. Consumptive use of this water through evapotranspiration will ensure crop growth and determine the yield level.

5.5 Conservation farming as a rainwater harvesting technique for sustainable agriculture in semi arid Zambia: A case study

Introduction

In Zambia, one of the biggest constraints in crop production is the uneven distribution of rainfall with some parts experiencing an almost perpetual inadequacy of the resource. The Country is divided in three main Agro Ecological Zones I, II and III according to the amount of rainfall received. Zones I and II are often affected by mild to severe droughts that lead to unpredictable, and mostly very low crop yields. The low yields from these zones cause significant detrimental effect in the food security of the country as a whole as the commodity has to be found else where to supplement the shortfall. Worse still, the areas affected are mostly in rural settings where the inhabitants have almost no financial strength to buy food throughout the year. Over the years, Conservation Farming has been introduced and encouraged in Zambia, mostly through the ministry of Agriculture and Cooperatives. This method of farming aims at mitigating inadequate rainwater resources and is adapted as part of integrated watershed management process.

Surface runoff in Zambia is generally in the range of 19–25% of precipitation (much higher for individual rainstorms), which is a result of crust formation, high intensity rainfall events and poor canopy coverage of the soil. Soil evaporation losses range from 30 to 50%. This is usually higher for degraded lands and lower for productive land (Rockstrom, 1999). The character of tropical rains, with large volumes falling in short time spans, also leads to significant drainage flow even in dry land amounting to some 15 –30% of rainfall. In total, this means that only 15–30% of the rainfall is directly used for production of biomass through rainfed agriculture. This analysis of rainfall partitioning indicate that water scarcity which is often the major constraint in crop growth in Regions I and II is not necessarily caused by low cumulative volumes of rainwater, but rather, the result of poor distribution of rainfall, large evaporative demand of the atmosphere and large losses of water in the water balance.

The Zambian experience

In recognition of the food security problems related mainly to the Agro Ecological Zones, a collaborative conservation-farming programme involving the Government, led by the Ministry of Agriculture and Cooperatives, on one hand and the private sector, on the other, was initiated. Agro Ecological Zones I and II, which are often adversely affected by the severe droughts, are the main targets of the programme. These zones accommodate about 70% of all the smallholder farmers of the country, and are the main cereal production areas of Zambia.

A conservation-farming project was established during 1996/1997 between Golden Valley Research Trust (GART) and Conservation Farming Unit (CFU) of the Zambia National Farming Union (ZNFU) working with groups such as CLUSA in Mumbwa working with DUNAVANT for cotton farmers, the Agricultural Support Program (ASP), GTZ, HODI (Formally Harvest Help UK). One of the main tasks was to test selected hand hoe and animal powered tillage systems, with a view to promoting sustainable crop production systems. Table 1 shows, small-scale crop yields in Zambia are often too low to support the livelihood of an average family.

Table 1: *Crop yields for smallholder farmers in Zambia*

Crop	Average Yield (kg/ha)	Acceptable Yield (kg/ha)	Good Yield (kg/ha)
Maize	1100	3500	5000
Groundnuts	500	1500	2000
Cotton	450	900	1500
Sunflower	400	1000	1500
Soya Beans	400	1200	2000

Source: Conservation Farming Handbook for Hoe Farmers in Agro Ecological I and II (2003)

In the last few decades, there has been a significant decline in the use of draft animals in regions I and II due to Corridor Disease. This forced farmers to adopt the Holey Ground or ripping conservation farming methods. On the social side, there has been significant decline of active farm labour due to urban drift and the influence of HIV/AIDS. The trend of food production, particularly Zambia's staple food-maize, over the past two decade shows insufficient total production and a decreasing output (table 2). The trend of food production shows insufficient total production. The present food insecurity and the projected population increase of 3.2% per annum in Zambia demand more productive and sustainable systems.

Table 2: *Estimated actual vs. Potential Yields for maize in major production Areas (Tones/ha)*

Location	Smallholder		Emergent		Commercial	
	Actual	Optimal	Actual	Optimal	Actual	Optimal
Mazabuka	1.8	3.2	2.3	3.6	4.5	8.1
Mkushi	2.2	3.2	2.6	3.6	5.4	8.1
Kasama	2.0	3.2	2.4	3.6	-	-
Chipata	2.2	3.2	2.6	3.6	-	-

Source: Maize Marketing Base line Study for Zambia (2003)

Conservation Farming Methods encouraged for smallholder farmers in Agro Ecological Zones I and II can be divided into two: Hoe Farmers that include holey ground, fertility pits and fertility furrows; and Farmers using Oxen (Ripping) that include Shaka tine, Magoye ripper and Palabana subsoiler.

Holey Ground

The land is prepared by a hand hoe based minimum tillage technology. Each basin is dug at 30 cm long, 15 cm wide and 20 cm deep. Workers are able to dig 200 basins in 4 hours. The basins are spaced 90 cm between rows and 70 cm between plant stations giving a total of 15,800 basins per hectare. When rainfall is low, potholes are dug between planting holes to harvest rainwater. Potholes are dug one meter apart along the crop inter-row as part of the first weeding. They should be about the same size as basins and left open. Potholes will harvest rainfall and thus reduce crop stress when there are long gaps between rains.

Fertility pits are dug with dimensions of 120-200cm diameters and depths of 60cm. Organic matter is added and compressed until the pits are full. Top soil is then poured on top. Once ready, plants are planted without any addition of inorganic fertilizers. Yields in such pits are said to be very high due to fertility improvement. Farmers have reported that the fertility in terms of improved yields is stable for about 5 years. These pits are also water-harvesting structures improving water retention and maintaining moisture even in times of low rainfall.

On the other hand, fertility furrows are made by the Magoye ripper with attached wings. The resulting soil profile is a depression in the middle. Organic matter is added into the furrow and covered. Different crop are planted to benefit from the improved fertility and moisture regime. The water collected ensures that the organic matter is broken down for slow release to the plants. The organic matter also improves the soil structure as well as the water holding capacity.

Ripping

Shaka tine – This was developed by the Dutch Gibson of CFU. It is fitted to an ordinary plough after removing the plough bottom. The machine works by ripping the soil which in effect cracks and breaks the hard pans..

Magoye ripper – The use of the Magoye ripper has gained ground. Its use has gone beyond the territory of Zambia where it was developed. It is often referred to as the Conservation Tillage tool for small scale farmers using animals.

Palabana subsoiler- This machine has not been very successful as a Conservation tillage tool because of its weight. It requires more power to pull.

Results from the Holey Ground Method

In a trial done by CFU, soil profiles were dug in cotton fields where holey ground was used and where cotton was planted after conventional ploughing. It was found that the soil water profile at the time of harvest was twice deeper in the holey ground method than in the conventional one (Gibson, 1999). In Malawi, results showed that tied ridges significantly increased yields of crops and economic returns to additional labour required on tied ridges for the maize crop. Tied ridges increased water infiltration and reduced soil erosion, thereby enhancing soil moisture regime (Chilimba, 1999). They also act as planting holes in the Holey Ground method.

Limited data from farmers has been collected from Chibombo, Monze, Mumbwa and Mazabuka districts. They are the yields of maize before and after adoption of conservation farming practice in the 1998 – 1999 seasons. Before farmers used conservation farming, their average yield was 7.68 ninety kilogram bags per Lima (1/4 hectare land) and the standard deviation was 3 bags. After farmers adopted conservation farming, the mean rose to 15.37 bags per Lima and a standard deviation of 5.83 bags (Langmead, 2001). These translates to yields of 2764.8 kg/ha before adopting conservation Farming and 5533.2 kg/ha after adopting Conservation Farming.

From work done by CFU at their demonstration farm at GART in Chisamba, a steady increase in yield has been noticed from 1.6 tons/ha to 6 tons/ha in 5 years. The demonstration farm is not only for conservation farming but also for Organic farming of all the crops grown in planting holes by CFU. Other NGO's like GTZ, HODI (Formally Harvest Help UK) in Namwala district are working with farmers in conservation farming.

Results from Golden Valley Research Trust (GART)

Deep ripping and basin planting are some of the emerging tillage practices in water management. Their superiority in maize yield as compared to other tillage systems (see Tables 3 and 4) has underlined the proposition that they have the ability to increase water harvesting, rainwater infiltration and thus water use efficiency. Notably the Magoye ripper has performed better than the Palabana ripper.

Table 3: *Tillage and Fertilizer Effect on the yield of Maize at Magoye 2000/2001 season*

Tillage System	Fertilizer (kg/ha)	No Fertilizer (kg/ha)	Increase in Yield (%)
Holey Ground	2875	612	369
Ploughing	2958	2010	47
Deep ripping (Palabana Subsoiler)	3250	796	308
Shallow ripping (Magoye ripper)	2567	531	383

Source: GART year book 2001

Table 4: *Effect of Tillage and Fertilizer Application on Maize at 12.5% Moisture Content at GART Chisamba for 2003/2004 season.*

Tillage System	**Grain yield (No fertilizer) (Kg/ha)**	**Grain yield (with fertilizer) (Kg/ha)**
Planting Basins	5954	6265
Deep ripping	5574	5875
Shallow ripping	4917	5312
Ploughing	4900	5468
Ridging	4227	4626
Traditional	4064	3459

Source: GART year book 2004 (In print)

The trend is similar with addition of fertilizer for all tillage systems. Fertilizer use produces better yields than where fertilizer use is better utilized in conservation tillage perhaps due to the rainwater harvesting associated with those systems. For ploughing the yield increase is only 47% while in other methods, the yields go well beyond 300%. Results also indicated that fertilizer use in the ripped furrows and the holey ground basins are relatively efficient. Shallow and deep ripping had crop yield increase of 49% with Holey Ground method at Magoye having an increment of 40% (GART year book 2000). The concentration of applied nutrients and trapped moisture to the ripped furrows and Holey Ground basins could ultimately explain the better utilization of such inputs as observed from these results.

Direct ripping is the most suitable for maize. However, ripping 25 – 30 cm is suited for cotton and pigeon peas (Table 5). It ensured improved water infiltration and adequate water storage. This enabled roots to grow deeper with large volumes and eventually produce better crop yields. Roots of pigeon peas and cotton grow relatively deeper than maize and eventually produce better crop yields. Roots of pigeon peas and cotton grow relatively deeper than maize and their potential is fully exploited in an environment of deep tillage. Ripping also ensures the breakage of underlying soil pans and liberates root penetration.

Table 5: *Crop yields in tones / hectare under different Tillage Systems at Magoye (2002 – 2003 season)*

TILLAGE SYSTEM	Maize	Pigeon Peas	Cotton
Direct planting	0.97	0.93	0.86
Planting Basins (CFU)	1.11	0.97	0.93
Ploughing	1.14	1.29	0.79
Ripping (25 – 30 cm)	1.03	1.51	1.07
Ripping / Ridging	1.28	1.23	0.83
Direct ripping (15 cm)	1.32	1.11	1.02

Source: GART 2003 Year Book

In conclusion Langmead (2001), observed that conservation farming practice increases yields by around 78 percent which is significantly greater than in normal farming practice. In addition, Conservation Farming traps soil moisture to improve water availability. Keeping crop residue on the surface traps water in the soil by providing shade. The shade reduces water evaporation. In addition, crop residue slows runoff and increases the opportunity for water to soak into the soil. Further infiltration occurs owing to macropore channels created by earthworms and old plant roots. Continuous no till can often result in as much as 2 more additional inches of water available to plants in summer (USDA, 1998).

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Chapter 6

Rainwater management for livestock production

6.1 Overview

Rainwater management is probably the most neglected and misunderstood aspect of livestock production. Water management is the key to everything. Incorporating innovative rainwater management strategies into livestock production can be very beneficial. Today, many thousands of hectares in Sub-Saharan Africa consist of impermeable paving, dreary detention basins, compacted soils, turf grass and landscaping that require an inordinate amount of money, energy and non-renewable resources to maintain. Where rainwater harvesting and sustainable ecosystems are the basis for the planning and design of livestock production systems, such systems and the native flora and fauna could flourish side by side.

Arid and semiarid areas are home to one-sixth of the world's population, most of whom are poor agro-pastoralists who depend totally on renewable natural resources for their livelihoods. The inhabitants of these regions are among the poorest people in the world. Their poverty is partly caused by inadequate supplies of water for crop, livestock and other enterprises. However, the shortage of water is not due to low rainfall, as is commonly perceived, but rather by a lack of capacity for sustainable management and use of available rainwater. The most critical management challenge is how to deal with rainfall variability—short periods when there is too much water and long periods of too little water. Better management of available rainwater could help to reduce the occurrence, and mitigate the impact, of droughts during dry periods or in places with low rainfall.

The current approach to food security considers self-sufficiency at the household level and focuses on overcoming water limitations. Subsistence producers who lack water give priority to minimizing risks at the expense of increasing productivity and profits. This is a strategic survival mechanism but it denies people the opportunities of building the capital resources required to:

- invest in new technologies;
- participate in the market economy; and
- Protect against extremes of climatic and economic downturns.

The technologies and skills required to overcome the lack of water resources, and poor and extremely variable rainfall, although well known, are not available and widely used. As a consequence, water supplies for agriculture, drinking and sanitation, and the environment are critically low. Poor access to water is among the leading factors hindering sustainable development in semiarid and arid regions. Approaches to overcoming this problem include technologies for enhancing the productivity of water in rainfed production, rainwater harvesting and precision irrigation.

In the case of Noah, mentioned in the Bible, solutions to flooding were simple. Noah's instructions came from on high, down to the last cubit. Once he had gathered two of all the animals in the ark, the rest was smooth sailing, so to speak. Floods are still a problem now. But in this day and age, what is needed is not an ark, but intelligent land planning and rainwater management. These techniques will help farmers enlarge their flocks of livestock to an extent which may now seem to be impossible.

Techniques to improve rainwater management, such as bio-swales that allow rainwater to seep into the ground as it flows away from parking lots, porous pavements, rain gardens and perforated diffuser pipes to capture and slowly dissipate water, are all readily available. However, people need to be made aware of them and educated about them.

6.2 Challenges and opportunities

Like humans, animals need water for drinking. Water is also needed to grow animal feed. Producing animal feed requires as much water as producing food for humans. The Nile Basin holds over 58 million tropical livestock units (TLU), comprising cattle, sheep, goats, camels, horses, donkeys, pigs and poultry (Table 4). The water required to produce feed crops for these animals amounts to 26 million m^3/yr. Previously, water productivity concepts were mainly applied to crop production. But, as the demand for milk and meat is projected to double over the next 20 years, livestock production needs to be factored into assessments of water use and productivity.

Table 4: *Estimates of tropical livestock units (TLU) in river basins in Nile riparian countries*

Country	TLU	Country	TLU
Sudan	23,237,976	Tanzania	4,790,060
Ethiopia	11,712,283	Rwanda	638,544
Egypt	6,521,339	Eritrea	627,170
Kenya	5,281,630	Burundi	278,544
Uganda	5,192,513	Congo	83,800
Total			58,360,359

One of the greatest development challenges in Sub-Saharan Africa (SSA) is to get well-known rainwater management practices adopted widely. The prospect of earning a sustainable income and making profits are among the most significant incentives for investing in any technology. Therefore, to improve the effectiveness and profitable use of rainwater and other resources in SSA for livestock production, the emphasis should be on incomes and profits. Furthermore, efforts should be directed at reducing risks and 'shocks' in SSA. Improved rainwater management has a vital role to play in reducing the risks to livelihoods and enterprises caused by climate variability.

Improving animal health, nutrition, management, marketing, housing and breeding are critical if producers are to increase stocking rates, switch to more intensive livestock (pigs and poultry) production and increase the amount of inputs used per animal. Changes in livestock systems include shifting from purely grassland-based systems to agro-pastoralism and mixed farming and, therefore, to purchased feed and intensive animal production systems.

One approach to effective management of rainwater involves intensifying livestock production. This means increasing variable inputs and, therefore, output per hectare of land. Intensification also includes increasing the cropping frequency, for example by reducing the length of fallows or by sequential cropping. This also requires an increase in variable inputs. The biomass produced directly from the land is then fed to livestock to produce second stage products, such as meat, milk and eggs.

For grassland-based systems with ruminant cattle, sheep or goats, the first stage of intensification generally involves increasing the stocking rate. The second stage of intensification also involves increasing the levels of inputs used (such as feed concentrate or veterinary treatments) and increasing the output per animal. Input requirements and product output differ substantially between different types and species of animals and even between age cohorts within a specific system. Stocking rates, inputs and outputs are often given in tropical livestock units (TLU) or livestock units (LU), in which the standard unit is a milking cow. Conversion factors are necessarily crude but are generally based on the metabolic weight of the animal, which reflects the nutritional energy requirement. For example, a sheep or a goat is usually represented as 1/8 LU, while a cow represents 1 LU. In intensive commercial pig and poultry production systems—often described as landless—there is no direct link between the inputs used per hectare of land and the quantity of meat, milk or eggs produced.

6.3 Classification of livestock production systems

Taking into consideration a range of criteria, including integration with crops, relationship to land, agroecological zone, intensity of production and type of product, livestock production can be classified into three main systems:

- Grassland-based systems, in which more than 90% of the dry matter fed to animals comes from rangelands, pastures or homegrown annual forages and where annual average stocking rates are less than 10 LU per hectare.
- Mixed farming systems, in which more than 10% of the dry matter fed to animals comes from crop by-products, or more than 10% of the total value of production comes from non-livestock farming activities. This category is subdivided into:
  - rainfed mixed farming systems, and
  - irrigated farming systems.
- Landless systems, which are based solely on livestock and in which less than 10% of the dry matter fed to livestock is produced on-farm. Annual average stocking rates are over 10 LU/ha.

These three types of system may be ranked in order of increasing intensity of production. Grassland-based systems are the least intensive, mixed farming systems are intermediate, while the landless systems are the most intensive. For the purposes of analysis, data on areas of permanent pasture, livestock numbers and production have been compiled for the main sub-continental regions in Africa: the northwest (Maghreb), west, central, east, south, and near east. The data represent the 10 years from 1988–1998 (Table 5).

Table 5 : Percentage growth in global livestock production (livestock output and number of animals slaughtered or milked) by region, 1988-1998

	Cattle		Milk		Pig		Chicken	
Region	Output	Slaught-ered	Output	Milked	Output	Slaught-ered	Output	Slaught-ered
Percent growth per year								
China	20.0	15.5	10.0	11.6	7.2	5.8	13.1	10.3
Other East Asia	3.3	2.0	8.1	3.0	5.6	3.5	8.9	8.4
India	3.6	2.2	6.4	1.6	2.8	2.8	11.9	11.9
Other South Asia	2.4	0.7	2.9	1.7	4.9	3.8	8.2	6.3
Southeast Asia	4.2	3.4	4.4	2.1	5.7	4.8	7.1	7.5
Asia excluding China	3.4	1.8	4.2	1.8	5.7	4.6	7.5	7.4
Latin America	2.1	1.8	2.5	1.8	0.1	-0.4	6.6	5.5
Sub-Saharan Africa	0.3	0.8	2.9	2.3	7.8	7.7	4.0	4.1
Developing world	3.0	1.5	3.8	2.0	6.1	4.8	7.3	6.9
Developing world excluding China	2.1	2.6	3.6	1.8	3.3	2.9	6.6	6.2
Developed world	0.1	-0.8	-0.4	-1.7	0.7	0.3	2.7	1.9
World	1.1	0.6	0.5	0.3	3.1	2.5	4.7	4.0

6.4 Livestock production and supply in Africa

In comparison with the rest of the developing world, African countries suffer a shortage of livestock products. Only in the southern countries of Lesotho, Botswana, Namibia and Swaziland do supplies of meat and milk per capita exceed the developing world average. Central Africa has the lowest per capita supply of livestock products.

The main sources of meat in Africa are cattle (41%), sheep and goats (22%) and poultry (25%). Dependence on ruminants, cattle, buffaloes (only in Egypt), sheep and goats (66%), is much higher than in the developing world (30%). Pig meat is as yet relatively unimportant in Africa (9%) while, on average in all developing countries, pig meat accounted for 42% of all meat supplies.

Table 5 compares the percentage growth per year in animals slaughtered or milked with the growth rate in meat and milk output, and indicates the contribution of improvements in productivity and increases in the number of animals to the growth in output. In Latin America and Sub-Saharan Africa, where land is relatively abundant, the growth in the number of animals contributed to increased livestock production. In these two regions, the number of cattle slaughtered or milked grew at rates nearly equal to or above the growth rate of beef and milk output, indicating that the number of animals contributed more to higher meat output than did improvements in productivity. The number of pigs grew at about the same rate as pork output in both regions, again indicating that the increase in production was due to the increase in the number of animals rather than to improvements in productivity. In Africa, the number of chickens grew at about the same rate as poultry output. In Latin America, the number of chickens grew more slowly than poultry output. Productivity is overall much higher in developed countries than in developing countries.

6.5 Livestock water use and livestock water productivity

Livestock water productivity in agricultural systems is the ratio of the sum of animal products and services produced to the amount of water required to produce them. Livestock water productivity assessments use quantitative indicators of animal outputs (e.g. kilograms of meat and manure, or hectares of land that oxen plough) or economic and social benefits that people derive from keeping animals.

Water accounting is a method of assessing the amount of water entering and leaving an agricultural system. It helps identify options for increasing water productivity, in order to increase animal production and decrease water depletion. The water accounting concept can be applied to fields, communities, watersheds or river basins. The challenge is to manage water, land and animals in ways that maximize the amount of water available for plant and animal production and environmental health, and decrease evaporation and harmful polluted discharges.

Water leaves an agricultural system as:

- evaporation from land, water and vegetation surfaces;
- transpiration from green plants, which drives photosynthesis and is essential for agricultural production; and
- discharge or physical flow.

A successful livestock enterprise requires a good water supply, both in terms of quantity and quality. While the quantity of water in Sub-Saharan Africa is known, the quality of water for healthy livestock production also needs to be evaluated.

Thus, managing rainwater for livestock production has two components:

- rainwater management for pasture production, and
- rainwater management for livestock consumption, in which water quality is a critical issue.

Rainwater management for pasture production

About 450 m^3 water per year is required to produce feed to maintain one TLU. This is the minimum amount. When animals are growing, working, stressed or lactating, they need even more. The quantity of water transpired in producing animal feed can be 50–100 times more than the quantity that animals drink. Although the amount of water drunk by animals is small when compared to the amount required to produce animal feed, and is essential for animal health and production, drinking water is not considered in water accounting because water consumed by an animal is not lost from the agricultural system.

Management practices for improved livestock water productivity

Feeding

Farmers grow forage crops both to feed their own animals and to sell. Efficient use of crop residues and by-products in animal production (Fig. 40) can increase food production and incomes without using more water. Well-managed grazing can make efficient and productive use of rainfall on land unsuitable for crops.

Figure 40: *Livestock feeding on crop residues*

Grazing

Overgrazing compacts soils, reduces plant diversity and increases surface water runoff. Optimal grazing conserves soils and encourages infiltration of rainwater, helping to prevent downslope flooding and sedimentation of reservoirs. Cut and carry feeding methods, combined with conservation tillage, reduce the water runoff and soil erosion associated with annual crop production and grazing livestock on the stubble that remains after harvesting. Application of manure also improves the capacity of soils to hold water.

Watering

Animals contaminate many water sources making the water unfit for human consumption. Simple measures, such as constructing drinking troughs for livestock, can prevent animals polluting domestic water supplies and transmitting water-borne diseases. Strategic development of groundwater for livestock could exploit underutilized pasture lands in large areas of Sudan and Ethiopia.

Figure 41: *Livestock at water points*

Feed, breeding stock and veterinary care

Many poor farmers lack good quality feed, breeding stock or artificial insemination services, and veterinary care. If these were available, farmers and herders could greatly increase animal production, water productivity and their returns on investments in water systems for agricultural production.

Marketing chains

Many areas suitable for livestock production are far from markets. Crop residues, crop by-products and irrigated fodder could be used to fatten animals and make them more attractive to international and urban buyers after their long trek to market. Ensuring water and feed supplies along the market chain increases opportunities for remote pastoralists and other producers who walk their animals to markets.

Resolving conflicts

Improved integration of livestock and water management can mitigate conflicts between herders and farmers in SSA.

Livestock–water interactions in agricultural production systems

Each of the many species and breeds of domestic animals in SSA interacts with water resources in a different way. Moreover, the inhabitants of different ecosystems use animals in different ways. One challenge is to understand how livestock water productivity within SSA varies from place to place, and the circumstances in which it leads to conflict and environmental degradation.

Irrigation systems

Although livestock densities in Africa are highest in or near large-scale irrigation systems, those who develop and maintain irrigation systems rarely integrate the needs for animal production or assess the impacts of these systems on displaced animal herders. When irrigation is successful, African farmers often choose to increase their livestock holdings. Even so, successful irrigation policy rarely includes providing the good quality feed, drinking water and veterinary care that domestic animals require. Consequently, animals kept in or near irrigation schemes tend to damage canals and reservoirs when they attempt to drink water and feed on riparian vegetation.

Mixed crop–livestock systems

Most African rural poor practice mixed crop–livestock production in rainfed systems. These rainfed crop–livestock systems are second only to irrigated systems in terms of high livestock densities. Limited land constrains both food and feed production, but animals are vital in these systems for their manure and draught power for cultivation, as well as for food, farm power, transportation and the savings they traditionally represent. Providing new options for feeding and watering stock, such as new varieties of feed crops whose residues are more nourishing for ruminants and improved cut and carry feed strategies, coupled with rainwater harvesting, can improve both animal and water productivity in these mixed farming areas.

Poor households and communities can manage their livestock more effectively, and help increase their food production and cash incomes, by practicing water harvesting techniques. Feeding crop residues and watering livestock at drinking troughs could help dryland farmers and herders increase profits and, at the same time, improve returns on their water harvesting investments.

Pastoral systems

The extensive grazing lands of SSA support large numbers of animals. These lands effectively use rainfall that would be depleted through transpiration before they reach the river systems. But, as irrigation and rainfed crop production encroach onto these areas, herders lose access to dry-season watering and grazing. However, there are opportunities to avoid and resolve these conflicts by developing solutions that would safeguard and enhance herders' access to water and feed resources. Such solutions could include, for example, constructing water pans and earth dams to create watering and micro-grazing areas.

The benefits of managing livestock water productivity

Applying new technologies to livestock water productivity through integrated livestock and water management will help ensure more effective, equitable and sustainable use of water resources in the SSA region.

Rainwater management for livestock drinking water

Water consumption

Water consumption varies widely, as it depends upon physiological and environmental conditions, for example the type and size of animal, whether or not it is lactating, how active it is, the type and amount of food it consumes, and climatic conditions. Estimating rates of water consumption is, therefore, subject to considerable error. The normal range of water consumption for adult animals has been summarized as follows (Table 6).

Table 6: *Livestock water consumption (Peden, 2003)*

Livestock type	Water consumption in litres/day
Beef cattle	35-60 per head
Dairy cattle	30-80 per head
Horses	24-36 per head
Swine	15-25 per head
Sheep and goats	5-20 per head
Chickens	40-50 per 100 birds
Turkeys	40-75 per 100 birds

Factors in water quality

The origin of all waters is rain and, because of this, most groundwater or surface water is satisfactory for livestock. Some water, however, is of poor quality resulting in poor performance or even death of animals. Excessive salinity—a high concentration of dissolved salts—makes water unsatisfactory for livestock. Water quality for livestock may also be affected by nitrate content, alkalinity and other factors.

Salinity

Water is a very good solvent, and all natural waters contain dissolved substances. Most of these are inorganic salts, calcium, magnesium and sodium chlorides, sulphates and bicarbonates. Occasionally the salts are present in such high concentrations that animals do not thrive, become ill or even die. The various salts have slightly different effects, but these differences are of no practical significance. Thus, while sulphates are laxative, and may cause diarrhoea, their effect on animal seems no greater than that of chlorides, and magnesium salts seem no more of a problem than calcium or sodium salts. Further, the effects of the various salts seem to be additive, which means that a combination of salts seems to have the same effect as that caused by a single salt at the same total concentration.

Research on the effects of saline drinking water on livestock has shown that, at high (but not toxic) salt concentrations, water consumption increases, although the animals may at first refuse to drink for a short time when given saline water. On the other hand, at very high salinities animals may at first refuse to drink for a few days, but then drink large quantities in one go, leading to sudden sickness or even death. Older animals seem to be more resistant to the harmful effects of salinity than younger animals.

Anything causing an increase in water consumption, such as lactation, high temperatures or exertion, also increases the harmful effects of saline water. Animals seem to have the ability to adapt to saline water quite well, but abrupt changes in salinity may be harmful, while gradual changes are not. When they have an alternative source of water livestock will avoid excessively saline water.

However, animals suffering the effects of saline water are known make a rapid and complete recovery when given water with a low salt content. Plus, salt is sometimes added to animal feed to regulate water intake. Special care to provide drinking water with a low salt content should be taken in these instances.

Nitrates

Nitrate-poisoning in cattle was first observed around 1900 and, since then, there have been many cases. As a rule, poisoning results from eating forages with a high nitrate content. The nitrates are not very toxic in themselves, but bacteria in the rumen reduce the nitrates to nitrites, which then get into the bloodstream. There the nitrites convert the red pigment, haemoglobin, which is responsible for carrying oxygen from the lungs to the tissues, to a dark brown pigment, methaemoglobin, which will not carry oxygen. When this conversion is about 50% complete, animals become distressed and short of breath, and when conversion reaches 80% or more, they usually die of suffocation.

Non-ruminants may convert small amounts of ingested nitrate to nitrite in their intestines, but the amount so converted is not harmful. Under some circumstances nitrates in the diet may also interfere with the conversion of carotene to vitamin A, but an impressive amount of experimental data shows this to be of no practical significance. Further, the experimental evidence suggests that chronic nitrate poisoning does not occur in livestock, and that the young are no more susceptible to acute nitrate poisoning than are older animals. Nitrates are occasionally found at toxic levels in water. Nitrites are also often present, but not at levels dangerous to livestock. As a rule, water analyses include data on both nitrites and nitrates.

Sulphates

Experimental data on the effects of large amounts of sulphates in livestock drinking water are limited. Both sodium and magnesium sulphates are well-known laxatives. In humans, a sulphate content of over 250-600 ppm may have a temporary laxative effect, while over 700 ppm may have a persistent laxative effect. Research in South Dakota (USA) showed that water containing up to 3,000 ppm sulphates had no harmful effects on the rate or efficiency of weight gain or on faecal consistency, in gestating or lactating sows or on their litters up to 28 days of age. In weaning pigs, 3,000 ppm added sulphates did cause more scouring and less firm faecal consistency than in pigs receiving water without added sulphates, but the rate of weight gain and efficiency was essentially the same. Sulphates in drinking water should seldom be a problem for livestock if rations are adequately formulated. However, copper deficiency might be a problem with high sulphate levels in drinking water.

Alkalinity

Most waters are alkaline, which is fortunate since, if they were acid, they would corrode pipes and plumbing. Only in a very few instances has water been found to be too alkaline for livestock. Alkalinity is expressed either as pH or as titratable alkalinity in the form of bicarbonates and carbonates. A pH of 7.0 is neutral, below that is acid, and above that is alkaline. Most waters have pH values between 7.0 and 8.0, which means that they are very mildly alkaline and, also, that they contain only bicarbonates and no carbonates. As the pH goes up, the waters become more alkaline, and at values of around 10, waters are very highly alkaline and contain carbonates. Most waters have alkalinities of less than 500 ppm, and are not harmful. Excessive alkalinity in water can cause physiological problems and digestive upsets in livestock. The level at which alkalinity becomes a problem and its precise effects have not been thoroughly studied. Therefore, the establishment of guidelines for levels of alkalinity in livestock drinking waters is difficult.

Bacterial contamination

Bacterial contamination in livestock drinking water does not usually cause problems. Most water consumed by livestock has some degree of contamination from being impounded in depressions, tracks, dugouts or ponds. However, producers should be concerned if farm water supplies become contaminated by bacteria. The source of contamination should be determined and eliminated, particularly if humans also consume water from the system. While there is no meaningful laboratory method to measure contamination in water for livestock, it should obviously be avoided. A reasonable effort should always be made to provide animals with a clean and sanitary water supply.

Other factors

On rare occasions, water may contain or become contaminated with toxic elements such as arsenic, mercury, selenium and cadmium, or with radioactive substances. While these toxic elements may harm animals, the major concern is that an accumulation in meat, milk or eggs is unsafe for human consumption. Water needs to be analyzed for toxic elements if there is good reason to suspect that they are present in excessive levels.

Persistent organic pesticides contaminate most surface waters. However, the concentration is small (because of their low solubility in water) and they are not a problem for livestock.

Occasionally, heavy algal growths occur in stagnant or slowly flowing water bodies. Under some circumstances, a few of these species can be toxic. As there are no tests for these toxins at present, stagnant water should not be used for livestock.

Interpreting water analyses

Salinity

A guide to the use of saline water for livestock is presented in Table 7. Considerable judgment should be exercised in using this guide. The guide has reasonable safety margins built into it and, with rare exceptions, adhering to the recommendations should prevent death of livestock or economic losses.

Table 7: *Guide to the use of saline water for livestock and poultry (Peden, 2003)*

Total dissolved solids (parts/million)*	Comments
Less than 1,000	This water should be excellent for all classes of livestock.
1,000 to 2,999	This water should be satisfactory for all classes of livestock. Water approaching the upper limit may cause some watery droppings in poultry, but should not adversely affect the health or production of birds.
3,000 to 4,999	This water should be satisfactory for livestock. If not accustomed to it they may refuse to drink it for a few days, but they will adapt to it in time. If sulphate salts predominate, animals may show temporary diarrhoea, but this should not harm them. It is, however, a poor to unsatisfactory water for poultry. It may cause watery faeces and, particularly near the upper limit, it may cause increased mortality and decreased growth, especially in turkeys.
5,000 to 6,999	This water can be used for livestock, except those that are pregnant or lactating, without seriously affecting their health or productivity. It may have some laxative effects and be refused by the animals until they become accustomed to it. It is unsatisfactory for poultry.
7,000 to 10,000	This should not be used for poultry or swine. It can be used with reasonable safety for older, low-producing ruminants or horses that are not pregnant or lactating.
Over 10,000	This water is considered unsatisfactory for all classes of livestock.

* Electrical conductivity expressed in micromhos per centimetre at 25°C can be substituted for total dissolved solids without introducing a great error in interpretation.

Nitrates

Comments relating to the use of water containing nitrates are shown in Table 8. In using this table, it is important to take into account how the nitrate content is expressed in the water analysis report. Sometimes the nitrate content is expressed in parts per million (ppm) of nitrate nitrogen (NO_3N). In other cases, it is expressed as parts per million of nitrate (NO_3) or of sodium nitrate ($NaNO_3$). The relationship between these is as follows:

1 ppm of nitrate nitrogen = 4.43 ppm of nitrate or 6.07 ppm of sodium nitrate. When total dissolved solids are less than 1,000 ppm, or conductivity is less than 1,400 micromhos/cm at 25°C, there is no need to make a nitrate determination.

Table 8: *Guide to the use of water containing nitrate for livestock and poultry (Peden, 2003)*

Nitrate content (ppm nitrate nitrogen)	Comments
Less than 100	Experimental evidence to date indicates that this water should not harm livestock or poultry.
100 to 300	This water should not by itself harm livestock or poultry. When feeds contain nitrates, this water could add greatly to the nitrate intake and be dangerous. This could be of some concern in the case of cattle or sheep during drought years and especially with waters containing levels of nitrates that approach the upper limits.
Over 300	This water could cause typical nitrate poisoning in cattle and sheep, and its use for these animals is not recommended. Because this level of nitrate contributes significantly to salinity, and also because experimental work with levels of nitrate nitrogen in excess of this are meagre, the use of this water for swine, horses or poultry should also be avoided.

Alkalinity

Waters with alkalinities of less than 1,000 ppm are considered satisfactory for all classes of livestock and poultry. Above that, they are probably unsatisfactory, although adults may not be harmed at concentrations of less than about 2,500 ppm unless the concentration of carbonates exceeds the concentration of bicarbonates.

Miscellaneous

Water may, in some instances, supply a part, or even all, of an animal's requirement for certain minerals. As a general rule, however, the contribution of water with respect to minerals is of no practical significance.

Hard water has often been said to cause urinary calculi (kidney stones or water belly). However, experimental evidence shows that this is untrue and that hardness might, in fact, actually prevent certain types of calculi formation.

Highly saline water is often mistakenly referred to as 'alkali' water. Saline water may or may not be highly alkaline, but usually is not. Sometimes saline water is referred to as hard water. If the salinity is in the form of sodium salts, however, the water may actually be soft, as hardness is due largely to calcium and magnesium.

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Chapter 7

Rainwater management for environmental sustainability

7.1 Overview

Overuse of river flow and groundwater aquifers—blue water resources—already occurs in much of the world. Current water abstraction focuses on the direct water requirements of humans and overlooks the water requirements of ecosystems.

Achieving ecologically sustainable food production requires the development of better ways to cope with a crucial set of challenging phenomena:

- Plant growth involves a biophysical process of consumptive water use, whereby huge amounts of water move from the soil to the atmosphere.
- Semiarid climates have particular challenges in meeting water requirements for grain production, combating drought and protecting against the risks posed by dry spells by using either large-scale or small-scale irrigation.
- Many tropical soils are particularly vulnerable to erosion, crusting and salinization.
- Since soil nutrients taken up by plants are carried away when the crop is harvested, they have to be replenished by application of fertilizers. Intensive crop production also puts high pressure on water resources and risks undermining the productive potential of soil.

7.2 The challenges

Massive reduction of land productivity in both irrigated and rainfed agriculture

More than 80% of the world's arable land suffers soil degradation, reducing its productivity. While a rate of erosion of 10 t/ha/yr is considered the absolute limit for sustained agriculture, erosion in semiarid tropical areas with intense seasonal rains may be as high as 30 t/ha per year. Where nutrient loss is not compensated for by application of fertilizer, or by shifting cultivation, nutrients are 'mined' from the soil. Over the last 30 years, nutrient levels have declined steadily in African soils. More than 10% of irrigated land is severely degraded by accumulation of salt; almost 30% is affected by both salinisation and water logging. Dryland salinity adversely affects agricultural or pastoral yields on some 3.3 million hectares, and, in 50 years, 17 million hectares will be at risk. Salinisation is also a common problem on over-irrigated land where appropriate drainage is absent.

Soil nutrient losses in Sub-Saharan Africa are an environmental time bomb. Unless these disastrous trends are reversed, the future viability of African food production systems will be imperilled, with severe socioeconomic impacts. The problems originate from the move away from shifting cultivation, which resulted in an agrarian crisis in Africa. In the temperate zone, this phase of agricultural development was accompanied by practices which first replaced nutrients with animal manure, and later replenished nutrients by applying fertilizers. Such developments in temperate areas led to current grain yields of 6–10 t/ha. However, nutrient losses in African farming systems have not been compensated for by new management strategies to maintain soil fertility. The productivity of African farming systems has, therefore, fallen, resulting in 'one-tonne-per-hectare agriculture'. African farmers often abandon degraded pastures and cropland and move to new land in response to declining soil productivity and low yields. From an economic point of view, it is cheaper for them to move to new land and exploit new resources rather than stay and rehabilitate already degraded lands.

Degradation of aquatic ecosystems

Reduced river flows, groundwater modifications and pollution contribute to large-scale degradation of aquatic ecosystems. The fragmentation of rivers, due to damming and physical alterations in river courses, also has negative effects. Furthermore, because people obtain many direct and indirect benefits from aquatic ecosystems, their degradation has a range of socioeconomic consequences, which may vary in severity.

Rivers

Stream flow depletion primarily affects downstream and delta ecosystems. Reduced sedimentation and accretion rates lead to coastal retreat and land subsidence. The use of fertilizers and pesticides threatens inland water bodies, such as lakes, with pollution and eutrophication.

Fishery resources

When aquaculture and shellfish opportunities in the lower course are affected by lack of water it translates to loss of revenue for riverine communities.

Wetlands and lakes

Groundwater-fed wetlands are vulnerable to groundwater extraction.

Coastal waters

Streamflow depletion and changing nutrient and sediment loads in watercourses alter coastal habitats and have major effects on coastal ecosystems. Eutrophication, over-fishing and aquaculture are major threats to marine biodiversity. A global assessment of key environmental problems showed that moderate or strong eutrophication affects 31 out of 88 coastal waters in the world, and water scarcity/streamflow depletion affects 30 regions. Pollution caused by agricultural nutrients has led to increased blooms of toxic algae in many coastal systems and to extensive dead zones in, for example, the Gulf of Mexico, the Black Sea and the Baltic Sea.

7.3 Opportunities to minimize environmental degradation

Securing minimum residual streamflows

Measures to counter environmental degradation include securing minimum residual flows (also called environmental flows), flood release and maintaining adequate flows for fisheries. Environmental flow requirements consist of ecologically relevant low-flow and high-flow components, and depend on the objective in terms of an acceptable conservation status (natural, good or fair).

In already over-appropriated rivers, minimum stream flow has to be secured by:

- either producing the same amount of food with less evapotranspiration and allocating the water saved to rivers, or through fallowing land;
- reducing evaporation from soils, water bodies and high water tables; and
- reducing flows to sinks such as saline aquifers or by reducing drainage flows directed away from river systems and into the sea.

One of the biggest misconceptions is that increasing the efficiency of irrigation could save enormous quantities of water. In river basins, drainage flows are often not wasted but are reused. Efforts to save water thus need to be redirected at the three points above. More precise irrigation methods, such as drip irrigation, may not lead to real water savings (unless evaporation is reduced) but can boost yields, water productivity and reduce losses of fertilizer through leaching. Another measure to reduce the ecological impacts of consumptive water use in agriculture is short-term flood releases, which have been advocated since the 1980s. Artificial flooding over the past eleven years has led to dramatic recovery of the Diawling delta ecosystem in Mauritania.

Allowing for ecological water requirements

Ecological water requirements, known as 'environmental flows', are commonly defined as the flows that are necessary to sustain aquatic ecosystems and the valued goods and services that they provide—fisheries, ecotourism, flood plain agriculture and natural purification of water. Assessing the environmental flows of rivers and investigating the correlation between flows and fish catch are essential inputs to decisions regarding water resource allocation at the river-basin scale. An environmental flow assessment should take into account not only the quantity of water needed to maintain socially acceptable levels of ecosystem health, but also other important characteristics of the natural flow regime, such as frequency of flows, timing and duration of flow events, and rates of change.

There are many difficulties, however, facing assessment and implementation of environmental flows, including the lack of understanding among decision makers of the socioeconomic benefits associated with flows, a lack of political will to implement flow scenarios, the relatively new and complex tools for assessing water requirements, and the need for technical support and scientific data for effectively determining flow scenarios for each unique river system. Despite these challenges, future management of water must continue to work towards achieving a sustainable balance between water for agriculture and water for natural ecosystems that are dependent upon adequate river flows.

Minimizing nutrient losses

Optimizing water and nutrient use efficiency for good crop yields demands addressing both factors simultaneously. Applying too much water may lead to nutrient loss, especially of nitrates, through leaching. For phosphorus, however, it is erosion that causes losses . Methods are needed to efficiently close the cycle of nutrients from soil to livestock, and back to the soil. In the case of fertilizer, split applications balanced to crop needs are fairly easy to introduce and both improve yield and reduce net loss of nutrients. Drip irrigation is especially useful for split applications as the fertilizer can be dissolved in the irrigation water—'fertigation'. Wastewater reuse in agriculture is also increasing. It is estimated that up to 10% of all irrigation water used in developing countries is reused wastewater. In Addis Ababa, a system of using wastewater from public toilets is being tested to determine the effects of urine and faeces on agricultural production. On the positive side, this use of wastewater and nutrients contributes to livelihood opportunities; conversely, it may pose health risks.

Minimizing land degradation

Numerous programs and nongovernmental organizations (NGOs) are promoting the adoption of organic and low external input methods to replenish soil fertility. These methods include incorporating leguminous trees and shrubs into improved fallow systems, planting leguminous cover crops, applying manure and compost, and biomass transfer. Maintaining soil organic matter (SOM), which has a number of important functions, is a delicate task in tropical agriculture. Net losses of several hundred to thousands of kilograms of carbon per hectare per year are common in tropical countries. Strategies that improve SOM levels include the following: no or minimum tillage, improved fallows using leguminous species, meticulous caretaking of crop residues and manure, applying inorganic fertilizers to increase crop residues and yields, and agroforestry.

Agro-ecological approaches have achieved encouraging results in Africa, for example in cropping systems where legumes are intercropped with cereals, and compost is used to restore soil fertility. There are, however, constraints to these approaches: they are very labour intensive, for example composting, manuring and biomass transfer is time-consuming and costly. Yet, such approaches worldwide have helped 11 million farmers, working a total area of 32 million hectares, to increase yields by at least 60%. Key elements in success were reducing the risks posed by drought and adopting innovative practices to reverse soil degradation while maintaining or enhancing food security. Community-based projects were generally at the catchment-scale. In development projects, leadership, social capital and community participation were the three most important elements. Technology-driven successes were generally led by individual farmers with secure access to land. However, without external support (financial and otherwise), the ability to replicate and scale up these successes will be restricted.

Infrastructure development should also be enhanced. If capital is the major constraint, increasing credit to farmers or cost sharing as a short-term strategy should be considered. Some experts suggest that the debate on (selective) subsidies for fertilizer, and even soil conservation measures that are a net benefit to society should be reopened. Research and technical assistance programmes that will investigate and promote use of fertilizer and other inputs must also be explored.

Balancing agricultural production with protection of aquatic ecosystems

A strategy for the integrated management of land, water and living resources, developed with stakeholder participation, will have to address the challenge of resolving conflicting interests between fisheries and various sectors concerned with human development and environmental conservation. Management of water resources in the regions requires a thorough understanding of hydrology, and the economic, policy and legal aspects of water management. The Commonwealth Scientific and Industrial Research Organisation, Australia, has developed innovative hydrologic, economic and community education tools for natural resources management. These models and community participation activities are readily transferable to other parts of the world.

Awareness raising

Although it is increasingly felt that ecosystems should be seen as forming an important component of 'water infrastructure', water decisions have in many cases proved to be financially and economically inappropriate. Ecosystem degradation leads to declining profits, increasing costs and the need for additional remedial measures. Economics are a powerful factor in decision making. Payments for ecosystem goods and services can highlight the linkages between upstream and downstream uses and impacts. Quantification of ecosystem benefits allows comparisons with other economic sectors and activities. Economic valuation can thus provide a convincing argument for placing ecosystems on the water and development agenda.

Coordinating land and water governance

Since practices upstream directly influence flows downstream, and thus wetland ecosystems and delta regions, integrated approaches for entire river basins are needed. Integrated Water Resources Management (IWRM) is recognized as a fundamentally important approach to sustainable development. Securing the environmental flows needed is, however, complicated since it is not in the mandate of one single decision-making body. Translating environmental objectives into well-defined and quantitative measures that can be used in mathematical modelling and optimization tools to evaluate the effect of different management policies is also a challenge. Such models would be helpful in helping negotiators and policy makers understand and assess options for environmental flows.

7.4 Technological options for ecological and ecosystem sustainability

Artificial groundwater recharge

The increasing demand for water has increased awareness of the use of artificial recharge to augment groundwater supplies. Stated simply, artificial recharge is a process by which excess surface water is directed into the ground—either by spreading on the surface, by using recharge wells, or by altering natural conditions to increase infiltration—to replenish an aquifer. It refers to the movement of water through man-made systems from the surface of the earth to underground water-bearing strata where it may be stored for future use. Artificial recharge (sometimes called planned recharge) is a way to store water underground in times of water surplus to meet demand in times of shortage .

Direct artificial recharge

Spreading basins

This method involves surface spreading of water in basins that are excavated in the existing terrain. For effective artificial recharge, highly permeable soils are suitable and the maintenance of a layer of water over these highly permeable soils is necessary. When direct recharge is practiced the amount of water entering the aquifer depends on three factors: the infiltration rate, the percolation rate, and the capacity for horizontal water movement. In a homogenous aquifer the infiltration rate is equal to the percolation rate.

At the surface of the aquifer however, clogging occurs through the deposition of particles carried by water in suspension or in solution, or through algal growth, colloidal swelling and soil dispersion, microbial activity, etc. Recharge by spreading basins is most effective where there are no impeding layers between the land surface and the aquifer and where clear water is available for recharge; however, more turbid water can be tolerated than with well recharge. A common problem in recharging by surface spreading is the clogging of the surface material by suspended sediment in the recharge water or by microbial growth. In coarse-grained materials, removal of fine suspended sediment is difficult.

Recharge pits and shafts

Conditions that permit surface spreading methods for artificial recharge are relatively rare. Often layers of low permeability lie between the land surface and water table. In such situations artificial recharge systems such as pits and shafts could be effective in penetrating the less permeable strata in order to access the dewatered aquifer. The rate of recharge has been found to increase as the slopes of the sides of the pits increased.

Unfiltered runoff waters leave a thin film of sediment on the sides and bottom of the pits which require maintenance in order to sustain the high recharge rates. Shafts may be circular, rectangular, or of square cross-section and may be backfilled with porous material. Excavations may terminate above the water table level or may be hydraulic connectors and extend below the water table. Recharge rates in both shafts and pits may decrease with time due to accumulation of fine-grained materials and the plugging effect brought about by microbial activity (O'Hare *et al.*, 1986).

Ditches

A ditch could be described as a long narrow trench, with its bottom width less than its depth. A ditch system can be designed to suit the topographical and geological conditions that exist at a given site. A layout for a ditch and a flooding recharge project could include a series of ditches trending down the topographic slope. The ditches could terminate in a collection ditch designed to carry away the water that does not infiltrate in order to avoid ponding and to reduce the accumulation of fine material (O'Hare *et al.*, 1986).

Recharge wells

Recharge or injection wells are used to directly recharge water into deep water-bearing zones (Fig. 42). Recharge wells could be cased through the material overlying the aquifer and, if the earth materials are unconsolidated, a screen can be placed in the well in the zone of injection. In some cases, several recharge wells may be installed in the same borehole. Recharge wells are suitable only in areas where a thick impervious layer exists between the surface of the soil and the aquifer to be replenished. They are also advantageous where in areas where land is scarce. A relatively high rate of recharge can be attained by this method. Clogging of the well screen or aquifer may lead to an excessive build-up of water levels in the recharge well. In ideal conditions, a well will accept recharge water at least as readily as it will yield water by pumping. Factors that cause the build up of water levels in a recharge well to be greater than the corresponding drawdown in a discharging well may include the following:

- Suspended sediment in the recharge water, including organic and inorganic matter;
- Entrained air in the recharge water;
- Microbial growth in the well;
- Chemical reactions between the recharge water and the native groundwater, the aquifer material, or both;
- Ionic reactions that result in dispersion of clay particles and swelling of colloids in a sand-and-gravel aquifer;
- Iron precipitation;
- Biochemical changes in recharge water and the groundwater involving iron-reducing bacteria or sulphate-reducing organisms;
- Differences in temperature between recharge and aquifer water.

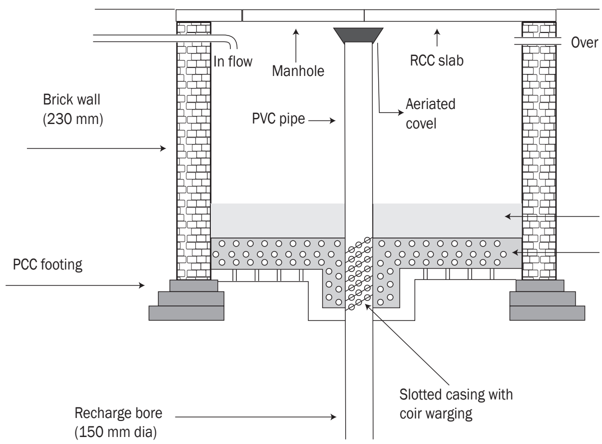

Figure 42: *Recharge well*

Factors that cause the build up of water levels in a recharge well to be less than the corresponding drawdown in a discharging well may include the following:

- Recharge water is warmer than native groundwater and therefore, less viscous;
- Increase in the saturated thickness and transmissivity of the aquifer due to the higher water levels that result when a water table aquifer is recharged;
- Recharge water that is unsaturated with respect to calcium carbonate. Such water may dissolve parts of a carbonate aquifer (O'Hare *et al.*, 1986).

Indirect artificial recharge

Enhanced streambed infiltration (induced infiltration)

This method of induced recharge consists of setting a gallery or a line of wells parallel to the bank of a river and at a short distance from it. Without the wells there would be unimpeded outflow of groundwater to the river. When small amounts of groundwater are withdrawn from the gallery parallel to the river, the amount of groundwater discharged into the river decreases. The water recovered by the gallery consists wholly of natural groundwater. Each groundwater withdrawal is accompanied by a drawdown in the water table. For high recovery rates this drawdown tends to lower the groundwater table at the shoreline below that at the river. Thus, surface water from the river will be induced to enter the aquifer and to flow into the gallery. In areas where the stream is separated from the aquifer by materials of low permeability, leakage from the stream may be so small that the system is not feasible (O'Hare *et al.*, 1986).

Conjunctive wells

A conjunctive well is one that is screened in both a shallow confined aquifer and a deeper artesian aquifer. Water is pumped from the deeper aquifer and, if its potentiometric surface is lowered below the shallow water table, water from the shallow aquifer drains directly into the deeper aquifer. Water augmentation by conjunctive wells has the advantage of utilizing sediment-free groundwater which greatly reduces the damage of clogging well screens. Other benefits are that:

- It reduces the amount of evapotranspiration water loss from the shallow water table.
- It reduces flooding effects in some places.

Environmental effects from the conjunctive well method must be carefully studied to assure that unwanted dewatering of wetlands or reduction of base flow will not occur. The possibility of coagulation due to mixing of chemically different groundwaters should also be investigated (O'Hare *et al.*, 1986; Table 9).

Table 9: *Some factors to consider for artificial recharge (O'Hare et al., 1986)*

1. Availability of waste water
2. Quantity of source water available
3. Quality of source water available
4. Resulting water quality (reactions with native water and aquifer materials)
5. Clogging potential
6. Underground storage space available
7. Depth to underground storage space
8. Transmission characteristics
9. Topography/applicable methods (injection or infiltration)
10. Legal/institutional constraints
11. Costs
12. Cultural/social considerations

Advantages and disadvantages of artificial recharge

Artificial recharge has several potential advantages:

- Aquifers can be used for the storage and distribution of water and removal of contaminants by natural cleaning processes which occur as polluted rain and surface water infiltrate the soil and percolate down through the various geological formations.
- The technology is appropriate and generally well understood by both the technicians and the general population.
- Very few special tools are needed to dig drainage wells.
- In rock formations with high structural integrity, few additional materials may be required (concrete, softstone or coral rock blocks, metal rods) to construct the wells.
- Groundwater recharge stores water during the wet season for use in the dry season, when demand is highest.
- Aquifer water can be improved by recharging with high-quality injected water.
- Recharge can significantly increase the sustainable yield of an aquifer.
- Recharge methods are environmentally attractive, particularly in arid regions.
- Most aquifer recharge systems are easy to operate.
- In many river basins, control of surface water runoff to provide aquifer recharge reduces sedimentation problems.
- Recharge with less-saline surface waters or treated effluents improves the quality of saline aquifers, facilitating the use of the water for agriculture and livestock.

Artificial recharge has some disadvantages too:

- In the absence of financial incentives, laws, or other regulations to encourage landowners to maintain drainage wells adequately, the wells may fall into disrepair and ultimately become sources of groundwater contamination.
- There is a potential for contamination of the groundwater from injected surface water runoff, especially from agricultural fields and road surfaces. In most cases, the surface water runoff is not pre-treated before injection.
- Recharge can degrade the aquifer unless quality control of the injected water is adequate.
- Unless significant volumes can be injected into an aquifer, groundwater recharge may not be economically feasible.
- During the construction of water traps, disturbances of soil and vegetation cover may cause environmental damage to the project area.

The hydrogeology of an aquifer should be investigated and understood before any future full-scale recharge project is implemented. In karstic terrain, dye tracer studies can assist in acquiring this knowledge.

Costs

The cost of treating wastewater to potable standards for agricultural purposes is generally prohibitive. Therefore, it is appropriate to consider whether an alternative approach would achieve reclaimed water storage needs without adversely affecting water quality, environmental, or public health.

The estimated cost of infiltration of surface water in Argentina, using basins and canals, is US\$0.20/m^3. The basins and canals used in a 1977 experiment in the San Juan River basin incurred a capital cost of US\$31,300. The comparable cost of watertraps in Argentina has been estimated at between US\$133 and US\$167. The capital cost of a 5,700 m^3 cutwater, equipped with a 14 m extraction well, is estimated at US\$6,325. The operation and maintenance cost is estimated at US\$248 per year. The production costs are estimated to be about US\$0.30/m for the first five years of operation, US\$0.17/m for the next five years (five to ten years of operation), and US\$0.15/m for the following five years (ten to fifteen years of operation).

In Jamaica, the initial capital cost of the sinkhole injection system established there was estimated at less than US\$15,000. This cost was primarily related to the construction of the inflow settling basin and channels conveying the runoff water to the sinkholes. Maintenance costs are low: less than US\$5,000 for the 18-month project (or under US\$3,500/year) (O'Hare *et al.*, 1986).

Soil conservation

The line between soil and water conservation (SWC) and rainwater harvesting (RWH) technologies for crop production is very thin. SWC can be described as activities that reduce water losses by runoff and evaporation, while maximizing in-soil moisture storage for crop production, but the same could be said of RWH. The two are differentiated by the fact that under soil and water conservation, rainwater is conserved in-situ wherever it falls, whereas under water harvesting, a deliberate effort is made to transfer runoff water from a 'catchment' to the desired area or storage structure (Critchley and Siegert, 1991). The important thing is that both systems complement each other, and under rainfed agriculture in dry areas, both are necessary nearly all the time.

Various interventions in SWC are implemented by farmers throughout East Africa, and they also form the foundation of many development projects with agriculture and land management on their agendas (Reij *et al.*, 1996; Lundgren, 1993; Hurni and Tato, 1992; WOCAT, 1997). Indigenous and innovative technologies in SWC, RWH and soil nutrient management abound in East Africa (Mulengera, 1998; Reij and Waters-Bayer, 2001; Hamilton, 1997), some of which have proved easier to replicate, especially those that are applicable over diverse biophysical conditions and have low labour requirements. In Ethiopia, the more common methods of SWC, RWH and nutrient management include level contour bunds, grass strips, cutoff drains, hill terracing and graded bench terraces, while water harvesting is practiced in underground tanks, open pans and ponds, spate irrigation and in various tillage systems (Wolde-Aregay, 1996; Hurni and Tato, 1992). In Kenya, the more common methods include terracing, vegetative barriers, conservation tillage, runoff harvesting and innovative technologies that trap and retain soil, improve its fertility or facilitate soil-moisture conservation and storage—these take different forms and techniques (Critchley et al., 1994; Mutunga *et al*., 2001). In Tanzania, the main interventions have included the tapping of runoff from roads, diversion of surface runoff from rocky areas, footpaths, conservation tillage, pitting systems, bunded basins, ridging, terracing and various types of runoff farming systems (McCall, 1994; Reij *et al*., 1996; Hatibu and Mahoo, 2000). They are described in Chapter 4.

Silt borrowing and trapping

Soil borrowing from rich valleys to top-dress degraded areas has been used to rehabilitate degraded lands in Kenya and Tanzania. The Promoting Farmer Innovation (PFI) Project (Critchley *et al*., 1999) identified several farmers in both countries who were using soil-harvesting techniques to improve soil fertility and/or moisture retention properties (Mutunga *et al*., 2001; Critchley *et al*., 1999). In Mwingi District, Kenya, two farmers, Kamuti Nthiga and Manzi Kavindu were independently trapping the silt fraction of the flood waters from seasonal rivers with amazing success, to build up a soil layer for growing sugarcane and fodder grass. In Dodoma, Tanzania, Peter Wilson and Hosea Mhuma invented a system in which they would ferry soil using wheelbarrows from nearby hills to cover and reclaim eroded/gullied land, creating deep enough soil for irrigated high-value vegetables (Thomas and Mati, 1999).

Gully control and utilization

Gully erosion is a major problem in East Africa (Fig. 43), and with the high costs associated with gully rehabilitation, most gully control activities have, in the past, been implemented by the government or with external assistance. Moreover, most gullies lie on public land, e.g., grazing lands, footpaths and farm boundaries. As such, the responsibility for their rehabilitation is usually beyond the scope of the individual. Studies in the Kiambu District of Kenya (Mati, 1984) showed that over 50% of the gullies emanate from road drainage. Thus, in the early 1990s, soil conservation activities were introduced into road rehabilitation projects to protect land from damage caused by road drains (Mati, 1992). However, even then, the main aim was to drain away surface runoff, which was seen as a destructive problem. These perceptions were later changed in the early 2000s to embrace the concept of water harvesting, even from gullies, for productive purposes. At last a gully could be viewed as an asset, and this was recorded in many parts of the country.

Innovative farmers have been able to convert gullies into productive land in Kenya's Mwingi, Makueni and Kitui Districts (Mburu, 2000; UNDP/UNSO, 1999; Critchley *et al*., 1999). In one such case, farmer Mutembei Mwaniki of Mwingi reclaimed a gully with stone walls, well-designed and complete with side spillways, and thus established level beds for cultivation of field crops through the gradual accumulation of sediment. He used stone check dams to trap sediments in the gully, in stages. Whenever a layer of silt built up, he would increase the height over the existing stone check by about 0.3 m. At the deepest point, up to 3 meters of sediment had accumulated. The total area reclaimed was around 500 m^2. The rehabilitated gully supported the cultivation of bananas and papaya as well as green maize. He was successful in obtaining a good yield from his crops, even as his neighbours' crops failed.

Gully control activities have been undertaken in the Arusha Region of Tanzania (Assmo and Eriksson, 1994), where farmers have been innovative and successful in rehabilitating gullies on their farms and converting them to productive land. In Dodoma (Tanzania), farmer Raphael Chinolo and his wife controlled a gully system by planting bananas in deep pits (Critchley *et al.*, 1999). They would fill each pit with 20 litres of manure before planting. The pits capture runoff, but to give extra control of overland flow, they made terraces of earth bunds 0.6 m high, upon which they planted *makarikari* grass for stability. This way, they were able to stop gully development, increase crop production, improve soil fertility, harvest runoff water and reduce soil erosion.

Figure 43: *Gully formation and control*

In Ethiopia, gully control has been carried out mainly using stone check dams, with U-shaped and parabolic spillways. These check dams have been quite effective in smaller and average-size gullies, but bigger ones need more sophisticated control structures (Wolde-Aregay, 1996). In Tigray region, gully reclamation for productive purposes has been practiced with favourable agronomic results. This has improved the potential for successfully cultivating banana, elephant grass and sugarcane on previously gullied land, albeit with complex socioeconomic implications (SIWI, 2001). Unclear land tenure created various difficulties in privatizing the reclaimed gully, which led to the progressive abandoning of crop husbandry in the gullies. Vegetative gully control has not been popular owing to lack of materials and also due to the problem of free grazing. Another basic rule of gully control, that of avoiding ploughing right up to the edge of gullies, was not followed because of the small size of most landholdings (Wolde-Aregay, 1996).

Ngolo pits

The Wamatengo people of Matengo highlands in Mbinga District in Tanzania have a unique indigenous farming system, known as 'ingolu' or 'ngolo' or simply 'matengo pits'. This is characterized by a combination of soil conservation techniques of pits and ridges on slopes of about 35-60% (Temu and Bisanda, 1996). A major feature of the ngolo system is that the fields contain a large number of pits. This system can be classified as 'grassland fallow farming', although cropping is usually repeated for many years without fallow. It is also combined with a two-crop-rotation system in which beans (*Phaseolus vulgaris L.*) are planted in the late rainy season of the first year and maize in the following year. As the ngolo farming system is repeated in a 2-year cycle, and as maize and beans are the two main food crops for the people of Matengo highlands, they need to own at least two fields. In the event of a decrease in the maize yield, the field is fallowed for several years until it is fully covered with shrubs or tall grasses (Tarimo *et al.*, 1998). When a maize crop that has been grown under the ngolo system of farming was compared with a similar crop obtained through terracing methods (Edje and Samoka, 1996), the yield from the ngolo system was found to be superior.

The ngolo system is also characterized by its land use in the early rainy season of the first year. In the month of March, the men cut the well-grown weeds in a system known as '*ku-kyesa*' which requires cutting the weed as close to the ground as possible. The cut shoots are left for 2 weeks to dry. The dry shoots are next gathered up into lines by a billhook. The lines stretch both vertically and horizontally forming a grid of 1.5-2.0 m squares. The size of the square determines the density of the plant population. This task is called '*ku-bonga*,' and is performed by men. The well-ordered lines become a basic design for the following work. The shoot bundles forming the lines are called '*mabongi*,' and all weeds growing on the field and maize stalk residues are used to make them. Thereafter, the mabongi are covered with soil, forming ridges at most 20-30 cm wide and 10-20 cm high. The size of the ridge affects the density of the plant population and the water-holding capacity of the pit. After finishing '*ku-bonga*' on a specified area, women cover '*mabongi*' with small amounts of topsoil in a square. Then they broadcast bean seeds on the small ridges and cover the seeds with soil. Throughout the next dry season a ngolo field is kept fallow, and at the beginning of the rainy season, maize is planted on the ridges where beans had been grown. The seeds are sown along the contour line. When maize reaches 20-30 cm in height, the weeds are removed and the sediment at the bottom of the pits is dug up by a hoe and used to re-build the '*mabongi*.'

Constructed wetlands/infiltration zones

Constructed wetlands are artificial, shallow excavations which are designed, built and operated to emulate the natural functions of wetlands. They contain a bed of porous rock soil, gravel or ash of about 0.3 to 1.0 m in depth, and are constructed with peripheral embankment at least 0.5 m above the bed to contain storm flows and the accumulation of vegetation and influent solids. Emergent aquatic vegetation such as *Typha,* is planted within these basins to emulate the structure and function of swamps, marshes and other wetlands (Fig. 44).

Water quality improvement is accomplished through physical, chemical and biological processes operating independently, and through the interactions of the plants, media and micro-organisms. The vegetation physically obstructs flows and reduces water velocity, thereby enhancing sedimentation and the deposition of the contaminants carried by the water. The root systems improve soil permeability, transfer oxygen into the surface sediments, and provide increased surface area for the aerobic decomposition of organic compounds by micro-organisms and the chemical oxidation of many metal ions.

Artificial wetlands may take various forms but generally include a screening stage to separate settleable solids (which are sent to a drying bed prior to land disposal), a wetland cell, and an aeration and disinfection stage as shown in the schematic layout in Fig. 48. There are projects using this technology in Zimbabwe, Zambia, Kenya, Uganda and Mozambique.

This technology can be aesthetically pleasing, depending on the type of plants chosen. Wetlands provide a habitat for a wide range of birds, plants, reptiles and invertebrates. Where they are properly designed, they can also be used for recreational and educational purposes.

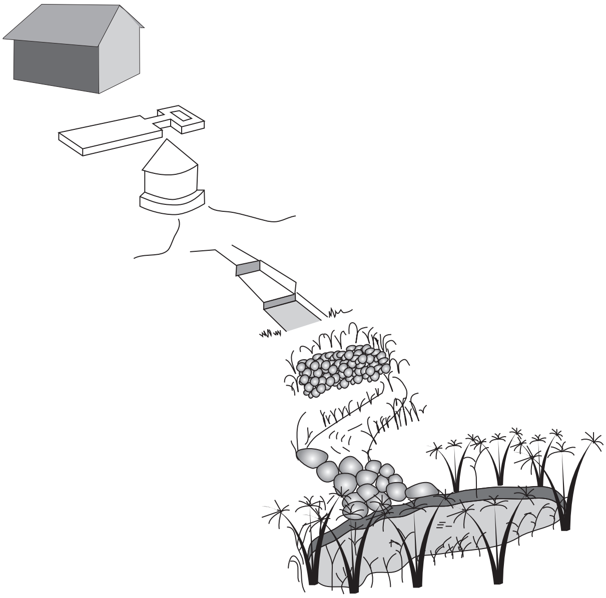

Figure 44: *layout and functions of a constructed wetland*

Agroforestry

Agroforestry (including social or communal forestry) is a multiple land-use system in which small-scale farmers raise tree crops with agricultural and animal crops (Benneh, 1987). Typically resource managers have identified agroforestry as a strategy for restoring degraded areas, increasing people's access to valued forest products, and conserving existing forest resources (Hough, 1991; Nair, 1990). In targeting smallholders, agroforestry has largely replaced industrial plantation-style forestry schemes. This change in approach arose because of agroforestry's potential for sustained improvement in rural living standards (Guggenheim and Spears, 1991; Cernea, 1991). Agroforestry strategies have recently focused on introducing nutrient-enhancing species that improve soil quality while providing tree products.

Benefits of multispecies agroecosystems

Multispecies agroecosystems are widespread throughout the tropics. In comparison with monocrops, such systems promise three benefits to farmers: increased productivity, increased stability and increased sustainability.

Increased productivity

This benefit concerns total productivity, which is normally higher than in monoculture systems: the output of valuable products per unit of land and labour is increased, through reduced damage by pests and diseases and through better use of resources. A multispecies system often has a green canopy that is denser for longer than that of a monoculture, allowing it to capture light that would be lost in monoculture. The mixed canopy may also reduce weed competition and reduce loss by evaporation directly from bare soil. A deeper and denser rooting system in a multispecies system may exploit the soil more completely, increasing the potential for water and nutrient uptake. Better soil physical properties and the reduction of runoff may conserve water, whereas enhanced soil biological activity and nutrient recycling may increase the availability of nutrients.

Increased stability

Sensitivity to short-term fluctuations is reduced by decreasing the risk of pests and diseases and by spreading those risks through species diversity. If one plant component fails to produce, the production of other plant components may compensate for it. In agroforestry systems, trees may increase the microscale variability in soil and in crop growth, which increases the probability that at least part of the crop will yield successfully.

Increased sustainability

Long-term productivity is maintained by the protection of the resource base. This may be the result of, for example, reduced erosion, input of nitrogen through biological N_2-fixation, retrieval of subsoil nutrients and/or reduction of nutrient losses through reduced leaching.

Simple agroforestry systems and agroforests

Simple agroforestry systems represent associations of a small number of components, usually no more than five tree species and an annual species (paddy, maize, vegetables, forage herbs) or a treelet (bananas, cocoa, coffee). These simple associations most often concern the 'agro-' facet of agroforestry, and the best-documented form of 'simple' agroforestry is alley-cropping. A famous simple agroforestry systems also concerns forestry, more precisely silviculture: the taungya system for the establishment of forest plantations. These simple agroforestry associations represent what can be called the 'classical' agroforestry model as it is the most favoured in research and development programs of most institutions dealing with agroforestry (Nair, 1989).

In complex agroforestry systems, a high number of components (trees as well as treelets, liana, herbs) are intimately associated, and the physiognomy as well as functioning of such systems is close to those observed for natural forest ecosystems, either primary or secondary forests. Because of the dominance of tree components, their high plant diversity and their forest-like structure and functioning, these complex systems, which we define as 'agro-forests', seem to concern more forestry scientists than agriculturists. However, they are not at all alien to tropical agriculture practitioners: agroforests characterize much peasant agriculture in the humid tropics.

This distinction between simple and complex agroforestry systems is not only academic, but also actually appears in present research and development programs. National and international institutions dealing with agroforestry research and extension most often only recognize simple agroforestry systems as true agroforestry. Most agroforestry projects concentrate on simple associations with fast-growing fuel-producing, soil-stabilizing or nitrogen-fixing tree species, either to diversify plantation agriculture or for reforestation and rehabilitation projects.

Unlike any other process of agricultural intensification, agroforests do not represent an irreversible specialization process. They allow the ecological potential of the site to be maintained and also allow economic options to be kept open for the future. Agroforests shelter potential economic resources which could be developed if the main economic crop fails; furthermore, new economic tree crops can easily be integrated without disrupting the overall structure of the production system. Agroforests can also provide or even generate valuable inputs (material, fertilizers, genetic resources) as well as capital (which can be used to further modify the system if necessary. This 'reversibility' of the conversion process is essential where one of the main concerns of farmers is to reduce risks of any kind.

Adoption and participation

Critical to conservation is that human activity must reduce pressure on existing resources. A vital component of any agroforestry project is that local people must identify an interest in obtaining trees.

One difficulty with conservation-related agroforestry is that the desire to plant trees corresponds primarily with international conservation goals, not necessarily with local perceived needs. As Kottak (1991) has found, projects that provide what people desire have a higher success rate than do those that propose solutions to problems local people have neither recognized nor embraced. People who recognize the need for trees engage more willingly in foreign-initiated agroforestry projects. Castro *et al.* (1991), for example, observed that certain Kikuyu in Kenya have practiced agroforestry for decades. They have actively sought solutions to their dual and contradictory needs for trees and land. In Haiti, people did not practice agroforestry, but their need for fuel wood became so severe that they welcomed the opportunity to experiment .

When using agroforestry as a means for conserving existing resources, then, projects may need either to generate an interest in tree-planting or to embellish fledgling interests. One of the difficulties, Cernea (1991) observed, is that a cognitive shift is necessary, where people see themselves as producers—not harvesters or gatherers—of construction and fuel wood.

Some scholars have found that where there are capitalist economic incentives and manageable risk, people are more likely to adopt agroforestry practices (Scherr, 1995; Suryanata, 1994; Tisdell and Xiang, 1996). Some have even stated that agroforestry programs must be economically attractive to be successful. Hosier (1989, p. 1835) stated that “it is the production from agroforestry systems that makes it an attractive land-use system for farmers, not its environmental benignancy.” However, Suryanata (1994, p. 1568) cautioned that although agroforestry works best when market demand exists for the products, “under market pressures, agroforestry loses some of the properties that earn it the reputation of being a sustainable system.” Caution must be maintained in balancing the benefits of marketing tree products with the costs, especially the potential increased pressure on both land and social relations.

Sometimes the sale of tree products is commercially viable. For example, Hosier (1989) found that people in Kenya grow trees for sale as poles used in construction.

7.5 Water management practices for ecological sustainability

The production of food and fibre often requires complex strategies that must balance profitable and efficient farming with water quality and quantity concerns. In irrigated crop production, water can be saved by improving supply channels, irrigation systems and water management. Because these issues are interrelated, and because financial resources are limited, and will therefore restrict progress, integrated approaches are required. Three water management practices are considered here: wastewater recycling, deficit irrigation and agronomic practices.

Wastewater recycling

Recycled wastewater is a potential alternative water resource for water-scarce regions. Treatment costs to purify wastewater to drinking water quality are high, but water of lower quality may still be used for irrigation purposes. Recycled wastewater is a valuable resource and is becoming more important, but plans for its use have to take into account potentially substantial secondary impacts.

Although views differ, researchers and health authorities say that it is possible to recycle water to the quality required for the intended use of the water—irrigation, horticulture, agriculture, household use, or drinking water. What is important is to define the standards for particular uses and then implement appropriate risk management, quality assurance and monitoring programs. The other vital issue to consider is how to convince the public of the benefits of using wastewater—addressing the ‘yuk’ factor in user perceptions might turn out to be the most crucial part of the whole process.

Strategies used in water recycling

Capture and recycle

The capture and recycle strategy, used in conjunction with other pollution-prevention practices, is an effective way to protect the quality of water supplies. Other advantages include lower water costs, an assured supply of good quality water and more flexibility in crop production. The major drawbacks of this strategy are the cost of building retention basins and storage ponds, and the potential impact on human health of using recycled water.

Collect and reuse/recycle irrigation water
This strategy involves capturing runoff and recycling irrigation water. Many greenhouse operations in Kenya have already adopted capture and recycling systems. Whether voluntary or mandated, these systems have environmental and monetary benefits. Greenhouse and other horticulture production operations that have adopted these practices state that the most important benefit is the savings on the cost of water. For other users, the most compelling reason for adoption has been to ensure that adequate supplies of sufficiently high quality water are available for production when needed.

Wastewater can be collected for reuse in retention basins, storage ponds and storage tanks. Concerns about, or potential disadvantages of, these systems are that they allow the concentration of salts, chemicals and nutrients; they also affect pH. If the wastewater is recycled back onto crops, these may affect crop quality. Studies have also shown that water-borne pathogens, such as *Pythium* spp., may be present in relatively high concentrations. Sometimes these pathogens can be detected in recycled irrigation water at the point of delivery to crops but, unfortunately, there are no scientifically derived thresholds for levels of pathogens in irrigation water. Because these contaminants may build up over time, many growers err on the side of caution by de-contaminating recycled water before reuse.

The potential disadvantages of using recycled water can be overcome by:

a) Monitoring salts, chemicals, nutrients and pH. Irrigation water should be tested three times a year for salt levels, bicarbonates, and pH. The results should be reviewed before any fertilizer is applied.
   - If a build-up of salts in recycled water becomes a problem, dilute with fresh water.
   - Many growers use water treated by reverse osmosis (RO) to remove potentially harmful salts. RO systems are relatively expensive but work well as a source of water for back blending. RO water has almost no nutrient content and, if used for an extended period, crops may suffer micronutrient deficiencies.

b) Proactive measures to deal with water-borne pathogens, such as *Pythium* spp., which may cause root rot:
   - Increase the frequency of scouting particularly-susceptible crops for problems.
   - Remove diseased plants from the system quickly.
   - Monitor pathogen levels of irrigation water. Sample water at different points to determine what pathogens are present and in what quantities. Tests to determine which pathogens are present can be conducted at plant disease testing laboratories.

- Treat water to remove pathogens by retention and dilution, filtration, chlorination, ozonation, and/or UV light.

Experiences from other regions

Research results from Tunisia and the Jordan Valley indicate that the impact of the use of treated wastewater on agriculture and rural development depends—at least in the short and medium term—on the socioeconomic and institutional environment of farming systems, rather than on the quality of the treated wastewater. Wastewater already amounts to around 5% of total available water resources in Jordan and Tunisia, and will increase to more than 15% within the next 30 years. The potential and limitations of this alternative water resource vary, because the contexts—farming systems and state of agricultural development—vary. Similarities are most likely to arise in the perceptions of consumers with regard to food produced by wastewater irrigation and less in wastewater use.

Administrative regulations and restrictions on wastewater use limit cultivation options in the Jordan Valley. The minimum size of farms has increased but the number of farms has decreased. Labour requirements in agriculture have fallen and the market supply of specific products has been affected. Tunisia, which applies comparable administrative regulations, intends to use wastewater as a first step in extending the area of arable land. This will raise income opportunities in farming systems based on agriculture, but may also limit opportunities for livestock owners, who currently rely on extensive use of communal land to graze their animals. The comparison of results from research in Jordan and Tunisia emphasizes the need for a thorough examination of each individual case before introducing or expanding the use of treated wastewater in agriculture.

Implementation of any new system inevitably means that there will be a learning curve. Potential problems that may occur with recycled water systems can be easily avoided with careful planning and investment.

Deficit irrigation

With increasing municipal and industrial demands for water, the allocation for agriculture is decreasing steadily. As most water in agriculture is used for irrigation, innovations are needed to increase the efficiency of the decreasing amount of water that is available. There are several possible approaches.

Improving irrigation technologies and irrigation scheduling may help use the limited supplies of water more rationally and effectively. Drip and sprinkler irrigation are more efficient than traditional surface irrigation. New irrigation scheduling approaches may not necessarily be based on full crop water requirements, but may be designed to ensure optimal use of allocated water. Deficit (or regulated deficit) irrigation is one way of maximizing water use efficiency (WUE) to obtain higher yields per unit of irrigation water applied: the crop is exposed to a certain level of water stress either at a particular stage or throughout the whole growing season. The expectation is that any yield reduction will be insignificant compared with the benefits gained by diverting the saved water to irrigate other crops. For successful deficit irrigation, the grower must have prior knowledge of crop yield responses to deficit irrigation.

Water is essential for crop production, and any shortage has an impact on final yields. Therefore, farmers have a tendency to over-irrigate, an approach that runs counter to the conservation of scarce resources. At present, because of the global expansion of irrigated areas and the limited availability of irrigation water, there is a need to optimize WUE in order to maximize crop yields under deficit irrigation. When water deficit occurs during a specific crop development period, the yield response can vary depending on crop sensitivity at that growth stage. Therefore, scheduling irrigation is important where a limited supply of water is available.

Water is a finite resource for which there is increasing competition among agricultural, industrial and domestic sectors. For example, in Mediterranean countries, Kemp (1996) states "The World Bank argues that the allocation of water to agriculture, which accounts for about 90 percent of regional water use, no longer makes economic sense… In Morocco, for example, it is estimated that the value added by a cubic meter of water in irrigated agriculture is a mere 15 cents; used in industry it is a striking $25. In Jordan, which uses highly efficient drip irrigation for over half of its irrigated agriculture, the equivalent figures are 30 cents for agriculture and $15 for industry."

Therefore, there is an urgent need to maximize crop yields when water supplies are limited. Regulated deficit irrigation at certain stages of maize growth can save water while maintaining yield. The upper limit for yield is set by soil fertility, climatic conditions and management practices. Where all of these are optimal throughout the growing season, yield and evapotranspiration are maximized. Any significant decrease in soil-water storage has an impact on water availability for a crop and, subsequently, on actual yield and actual evapotranspiration.

Deficit irrigation can be defined as an agricultural water management system in which less than 100% of the potential evapotranspiration can be provided by a combination of stored soil water, rainfall and irrigation, during the growing season. As water supplies decline and the cost of water increases, it is clear that producers are being driven towards deficit irrigation management. The implication of this management system is that some level of plant water stress is unavoidable. The challenge is to define a management system that will minimize the negative impact of the expected stress. Irrigation management requires choosing the timing and amount of water to be applied. Deficit irrigation management requires optimizing the timing and degree of plant stress, within the restriction of available water. This third, critical, concept greatly increases the complexity of the decision-making process.

The proper application of deficit irrigation can generate significant savings in irrigation water allocation. Among field crops, groundnut, soybean, common bean and sugar cane show proportionately less yield reduction than the relative evapotranspiration deficit imposed at certain growth stages. Crops such as cotton, maize, wheat, sunflower, sugar beet and potato are well suited for deficit irrigation, applied either throughout the growing season or at pre-determined growth stages. For example, deficit irrigation applied during flowering and boll formation stages in cotton, during the vegetative growth of soybean, the flowering and grain filling stages of wheat, and the vegetative and yielding stages of sunflower and sugar beet, provides acceptable and feasible irrigation options for limited supplies of irrigation water while resulting in minimal yield reduction.

Deficit irrigation management

Deficit irrigation practices differ from traditional water supply practices. The manager needs to know the level of transpiration deficiency allowable without significant reduction in crop yields. The main objective of deficit irrigation is to increase the WUE of a crop by eliminating irrigations that have little impact on yield. The resulting yield reduction may be small compared with the benefits gained through diverting the saved water to irrigate other crops for which water would normally be insufficient under traditional irrigation practices.

Before implementing a deficit irrigation program, it is necessary to know crop yield responses to water stress, either during defined growth stages or throughout the whole season (see Table 10 for an example). High-yielding varieties (HYVs) are more sensitive to water stress than low-yielding varieties. For example, deficit irrigation has been shown to have a more adverse effect on the yields of new maize varieties than on those of traditional varieties. Crops, or crop varieties, that are most suitable for deficit irrigation are those with a short growing season and tolerance to drought.

Table 10: *Expected relative yield and relative water use efficiency for a planned evapotranspiration (ET) deficit of 25%. Adapted from Kirda, 2002.*

Crop	Stage when ET deficit occurred	Irrigation method	Expected relative yield	Relative water use efficiency
Common bean	Vegetative; Yield formation	Furrow	0.86 0.78	1.14 1.04
Cotton	Whole season; Boll formation and flowering	Drip Furrow	0.79 0.88	1.05 1.17
Groundnut	Flowering	Furrow	0.82	1.09
Maize	Whole season	Sprinkler	0.82	1.09
Potato	Whole season; Vegetative	Drip Furrow	0.79 0.90	1.06 1.20
Soybean	Vegetative	Furrow	0.86	1.14
Sugar beet	Whole season; Mid-season	Furrow	0.79 0.84	1.05 1.12
Sugar cane	Tillering	Furrow	0.90	1.20
Sunflower	Whole season; Vegetative yielding	Furrow	0.77 0.79	1.03 1.06
Wheat	Whole season; Flowering and grain filling	Sprinkler Basin	0.81 0.90	1.08 1.20

In order to ensure successful deficit irrigation, it is necessary to consider the water retention capacity of the soil. In sandy soils plants may undergo water stress quickly under deficit irrigation, whereas plants in fine-textured deep soils may have ample time to adjust to low soil-water matric pressure, and may remain unaffected by low soil-water content. Therefore, success with deficit irrigation is more probable in finely textured soils. Under deficit irrigation, agronomic practices may require modification for example, by decreasing plant densities, applying less fertilizer, adopting flexible planting dates, and selecting varieties with shorter growth seasons.

Agronomic practices

It is of fundamental importance for crop production—whether irrigated or rainfed—to avoid latent water shortage during the most susceptible phases of yield formation. Agronomic strategies to save water can be developed according to the concept of the resource-use efficiency, or rather the water-use efficiency with its three components: *uptake-, conversion-, and transformation-efficiency.*

Improving uptake-efficiency is useful in locations where rainfall before or during the vegetative growth period saturates soil moisture down to deeper layers where it can be exploited by deep-rooting crops and, thus, bridge the lack of water later in the season. Developing varieties that are deep rooting and can increase water uptake can be achieved by agronomic measures or by breeding.

With regard to evapotranspiration-efficiency (ETE), the second component of WUE, differences among species are well known. Unfortunately, determinations of varietal differences are very laborious and time-consuming and, hence, rarely available. Varietal ETE can be indirectly determined by D ^{13}C-discrimination analysis. However, the instruments are expensive and sophisticated and use of this indirect method is not widespread.

The third WUE component is the harvest index, representing the efficiency of the transformation of biomass into yield. Since raising this index has been the basis for development of all high-yielding varieties, room for varietal improvement exists only in species that have not been subjected to intensive breeding.

Agronomic measures, such as varying tillage methods, mulching and applying anti-transpirants, can reduce the demand for irrigation water. Other practices, like pruning, weeding, pest control and early planting, are also known to reduce requirements for irrigation water.

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Chapter 8

Economics of Rainwater Harvesting

8.1 Introduction

The need for economic analysis

Worldwide today, especially in the arid and semiarid areas, rainwater harvesting (RWH) has become increasingly important for agricultural production and domestic use. For crop production, common rainwater harvesting practice is diversion of flood flows from gullies into crop fields and reservoirs, while for livestock production, the construction of small dams, such as *Chaco* dams, has been the main practice. For domestic use, the main practice is rooftop harvesting using a system of gutters and tanks. However, harvesting rainwater costs money. Farmers have to invest resources (land, labour and capital). Construction and maintenance of RWH structures is normally labour intensive. Structures, such as storage ponds for livestock use, bunded/*majaluba* basins for rice production, and tanks for domestic use may involve collective or hired labour. As a result, economic evaluation/analysis becomes important in the implementation of RWH.

What is economics?

Before going into the economics of RWH it is important to have an understanding of economics in general. Economics is a social science. It is defined as the study of how limited resources can best be used to fulfil unlimited human wants. Whereas the wants and desires of human beings are unlimited, the means or resources available to meet these wants and desires are limited. Economics is concerned with understanding the principles and developing rules to govern the production and consumption of goods and services in an economy, in order to make the best use of available resources. Specifically, the study of economics deals with understanding and modelling the behaviour of individual consumers and producers as well as the aggregate of all consumers and producers. The set of rules governing behaviour are represented as economic theories.

Some important concepts in economics

There are three important concepts in economics. These are scarcity, allocation, and goals or end objectives.

Scarcity

Most goods and services are scarce, including production inputs and consumption goods.

- Note that there are human needs/desires on the one hand, most of which are insatiable, and resources on the other hand, most of which are limited or scarce.
- Resources that are abundant, such as air, are free, while scarce resources are allocated based on a price mechanism or rationing.

Allocation

Since many resources are scarce and needs are unlimited, a mechanism is needed to guide the use of resources. This entails choosing the alternative which best reflects the real opportunity cost of the resource, and which is consistent with individual or social objectives. For example, a farmer may need to decide how much of one hectare of his land he should allocate to maize and how much to sorghum. Prices play an important role in the allocation of resources, as well as in the allocation of goods and services.

Goal (end or objective)

Goals represent the needs to be satisfied. Since individual needs or desires appear to be unlimited, goals compete for scarce resources. Indicators help in choosing among competing alternatives, for example prices, profits and utility. The goal is often to maximize or minimize these indicators, for example to lower prices or raise profits.

What is an economic problem?

For a problem to be economic, (1) scarcity and (2) alternatives must exist. For example, if there is scarcity but there are no alternatives, there is no choice to be made. On the other hand, if there are alternatives but no scarcity (the goods or resources are free), the problem is not an economic one. In both examples allocation would not solve the problem.

Is water a scarce economic resource?

Water qualifies as a scarce resource because:

- Competition between users for water means that water needs to be allocated.
- Water is not uniformly distributed and is therefore a scarce resource (where there is none or where there is not enough).
- Other resources are needed to make water available, for example water harvesting,

exploration and drilling for water.

- It is a resource/factor for production (similar to land, labour and capital). In the classical production function (Fig. 45) output increases as the water input increases, up to the point where more water input leads to lower output. The average product for water (APP, water) and the marginal product for water (MPP, water) can be derived from Fig. 49. The term 'APP, water' measures the efficiency of water use, while 'MPP, water' measures the change in output as a result of a unit increase in water.

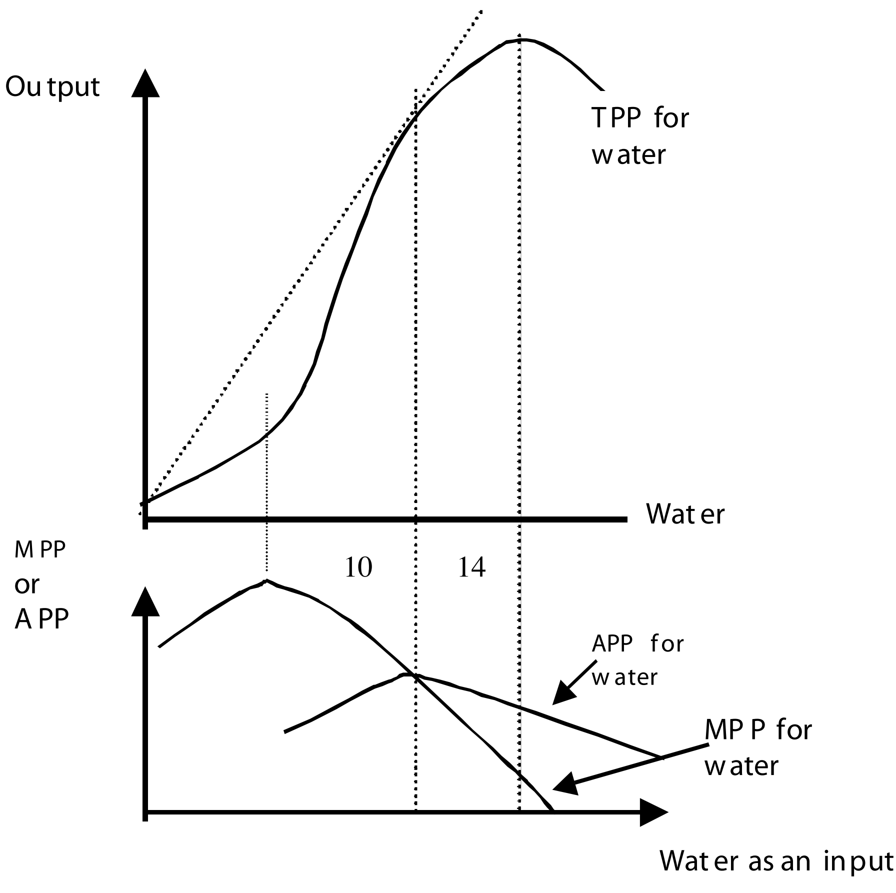

Figure 45: *Water as an input in the classical production function; TPP = total product, APP = average product, MPP = marginal product*

8.2 Economic evaluation of rainwater harvesting

Economic evaluation of RWH technologies ranges from simple yield comparisons to more sophisticated risk analysis methods, such as stochastic dominance analysis (Kunze, 2000). However, highly sophisticated techniques are normally limited by availability of data.

The most commonly used economic evaluations of RWH in Tanzania are yield comparisons (Rwehumbiza *et al.*, 1999; Hatibu *et al.*, 1999), gross margin analysis (Hatibu *et al.*, 2000) and investment analysis (Lazaro *et al.*, 2000). All the methods evaluate the 'with' RWH, 'without' RWH, and before and after RWH situations.

Yield comparisons compare RWH technologies. For example, in semiarid areas of Morogoro and Mwanga Districts, Hatibu *et al.* (1999) used yield comparisons to show that micro-catchment RWH is feasible during *vuli* short rains. Rwehumbiza *et al.* (1999) compared the yields of maize grown with stone bunding, contour ridge, and live barrier rainwater harvesting methods with yields of maize grown on the flat and with zero tillage. The results showed that, with rainwater harvesting, maize yields were 2.5–2.7 t/ha compared with 2.2–1.7 t/ha for flat cultivation and zero tillage. Yield comparisons can also be made using survey data; however, the accuracy of such data needs to be considered. Whenever possible, actual yield measurements should be taken to ensure accuracy.

Gross margin analysis

Gross margin is the difference between the gross value of output and the total variable costs used in the production process. Financial analysis in agriculture production is usually based on farm models. These models generate gross margins for enterprises (crops and livestock), allowing comparison of the situation 'with' the technology to that 'without' the technology. Gross margin analysis is static, and does not take into consideration the time value of money. This is a deficiency in gross margin analysis of RWH structures, which produce benefits over a number of years. However, gross margin analysis is a useful tool, which helps improve overall farm management as it addresses resource productivity over a given period of time. Hatibu *et al.* (2000) calculated the returns on RWH technology on maize and onion production in the villages of Hedaru and Mgwasi, in the Western Pare Lowlands. The results showed that the annual return on RWH in maize production[1] was lower than that in onion.

Investment analysis

Investment analysis spreads costs and benefits across the lifetime of the project, which in the case of RWH is always more than one year. The costs and benefits of bunded/*majaluba* fields, for example, may extend over 10 years or more. Lazaro *et al.* (2000) reported the results of an economic analysis of rice production in bunded/*majaluba* basins in Dodoma, Tanzania. The results showed that rice production in bunded/*majaluba* basins is profitable with a net present value (NPV) of Tanzania shillings (TShs) 84,349.9 at a 10% discount rate and TShs30,407.7 at a 24% discount rate.

Investment analysis needs to consider the following.

Evaluation criteria

Normally, the evaluation criteria include net present value (NPV), benefit–cost ratio (BCR) and internal rate of return (IRR). NPV is the discounted net benefits over the lifetime of the project. BCR is the ratio of discounted benefits to costs. IRR is the discounting rate that equates the NPV to zero. For small projects, such as water harvesting, IRR allows comparison with the official interest rate (Kunze, 2000). In West Africa, an IRR of as high as 45% was calculated for sorghum grown using stone dams (Kunze, 2000). In this study, NPV, BCR and IRR were computed as measures of project worth for maize, paddy rice and onion.

Time horizon

The time horizon selected will depend on the anticipated life of the project. It is generally argued that small-scale farmers have short time horizons and that this point of view has been a factor in determining the acceptance of long-term projects. Kunze (2000) recommended a time horizon of 10 years for RWH technologies, after which the structures may need to be re-constructed or undergo major rehabilitation.

Discount rate

The issue of discount rate is highly debated (Enters, 1998). For the purpose of analysing farm level projects, normally private interest rates are used. Investment calculations usually apply interest rates of between 5% and 15% (Enters, 1998). This study used a discount rate of 10%, which is considered to be the opportunity cost of capital. However, since many farmers may use local commercial banks, lending/discount rates of 20% were also used in this study.

Prices and valuation of labour

Prices play an important role in investment analysis. Normally, market prices are applied, although farmers may receive different prices for their produce at different times. For example, prices immediately after harvest may be lower than prices after the produce has been stored for some time. The decision to apply current prices as opposed to a constant price needs to be made beforehand, as it has implications for inflation in the calculation. Normally, constant prices are applied because it is assumed that inflation will exert the same relative effect on both costs and benefits (Gittinger, 1982).

Many investment analyses apply minimum wages and disregard the opportunity cost of labour. Minimum wages usually overestimate labour opportunity costs in rural areas. Some authors have suggested that family labour has an opportunity cost of zero. However, as noted by Kunze (2000), this is not the case even at high unemployment rates, because social activities—labour contributing to social security—imply an opportunity cost above zero.

The cost of hired labour varies with the seasons. During slack seasons, the cost is low. An average value (TShs1,000) for the two agricultural seasons (*Vuli* and *Masika*) was taken as the opportunity cost of labour in the study areas of Dodoma in Tanzania.

Sensitivity analysis
Sensitivity analysis systematically tests the earning capacity of a project during the planning process. It is a means of dealing with uncertainty about future events and values. As pointed out above, prices of agricultural products are highly variable due to seasonal supplies, their perishable nature and bulk. As a result, prices may change drastically over time. Sensitivity analysis tests the viability of project worth.

8.3 Planning and appraising rainwater harvesting projects

Planning and appraising RWH projects follows normal planning and appraisal processes.

Things to consider when planning and evaluating rainwater harvesting projects

Technical aspects

Consider inputs (supplies) and output (production).
Conduct a technical analysis of suitability, soils, slopes and the potential for RWH.
Consider institutional, organizational and managerial aspects:

- Is the institutional setting appropriate?
- Is the project manageable?
- Are lines of authority clear?
- Do you need monitoring groups?
- Are the staff able to manage the project? (If not consider training or hiring.)

Social aspects

Examine broader social implications:

- Income distribution.
- Upstream–downstream relationships.
- Quality of life—diseases, health, nutrition.
- Adverse impacts of the project—floods, pollution.
- Commercial aspects.
- Major commercial aspects:
  - Marketing outputs, market information, market forecasting,
  - Supply of inputs—fertilizers, construction materials.

Financial aspects

Determine the financial effects of the proposed RWH project on each participant.

Undertake a profitability analysis of the project—gross margin, budget analysis and investment analysis (discounted and non-discounted measures).

Economic aspects

Look at the contribution of the project to the economy as a whole. Does it justify the use of resources?

Consider externalities, such as external costs and benefits that may occur but are not planned.

Project appraisal

In appraising the project, review the project proposal, focusing on technical, commercial, organizational, managerial, financial and economic aspects, using economic and/or financial appraisal tools. Two appraisal methods are available: non-discount and discount.

Non-discount method of appraisal

The non-discount method of appraisal considers the payback period, that is, the number of years it will take to pay back the investment. This method allows projects to be ranked and is simple to apply but does not consider revenue after the payback period. It is not a measure of profitability but of liquidity.

Discount method of appraisal

The discount method takes into consideration the time value of money. These methods are more appropriate for appraising RWH projects because once an investment in RWH has been made it continues to confer benefits for a specified number of years. The most commonly used discount method of appraisal is the cost–benefit analysis (CBA). CBAs include the following:

(i) The 'with' and 'without' situation.
(ii) Estimates of the physical consequences over time.
(iii) Costs/benefit determinations of the physical consequences in order to derive cash flows over the life of the project.
(iv) Discount cash flows at market rates in order to derive measures of discounted project worth: the internal rate of return (IRR), benefit:cost ratios (B:C) and net present value (NPV). Discounting is an essential step in financial and economic analysis because this translates all future costs and benefits to present values. The present value is a common measure that can be used to compare projects of different life spans and gives the present value or worth of a future amount. The present worth of a future amount is determined by multiplying the future

amount by the discount factors. Discounting allows comparison of costs and benefits occurring at different times.

(v) Transform financial analyses into economic analyses by repeating all the steps above with the following modifications:
  a. Adjust for transfer payments.
  b. Use social opportunity costs/benefits.
  c. Discount at the social discount rate.

(vi) Perform a sensitivity analysis to find out the effects of changes in prices of inputs and outputs on the calculated measures of project worth.

(vii) Selection Principle/Ranking Principle:
  a. For the IRR, select the investment if, and only if, the IRR exceeds the cost of raising investment funds. Rank all investments in order of decreasing internal rate of return.
  b. For the NPV, select the investment if, and only if, the NPV is positive. If investments are substantially the same size, rank projects in order of decreasing NPV.
  c. For the B:C ratio, select projects whose C:B ratio is greater than one and rank all investments in order of decreasing B:C ratio.

Economic costs and benefits of rainwater harvesting

Costs vary with the nature of the project but, for RWH projects, the following costs are normally considered.

Investment costs

Investment costs are all the costs involved in setting up RWH systems, for example, design, construction, cost of water (water rights), and cost of the catchment area. It is important to consider the nature of the catchment and the alternatives available, and downstream–upstream relationships.

Annual costs

The annual costs are operating, maintenance, repair and input costs. Input costs may include labour, seeds, fertilizer, land, equipment and so on.

Externalities (indirect costs and benefits)

These are external costs and benefits that occur as a result of the project. They may be unplanned. For example, erosion, floods, silting of reservoirs and irrigation channels are externalities.

Benefits can be categorised into:

- Direct benefits—those accruing as a direct result of project activities, for example increased crop production as a result of RWH;
- Indirect benefits—such as the beneficial externalities mentioned above; and
- Intangible costs and benefits—those that are difficult to quantify, for example lives saved, environmental costs and benefits.

The 'with' and 'without' situations

Project analysis attempts to identify the costs and benefits of the proposed project (with) and to compare them with the situation as it would be without the project (without). The difference between 'with' and 'without' is the incremental net benefit from the project investment. This approach is not the same as comparing the situation 'before' and 'after' the project. The before and after comparison fails to account for changes in production that would occur without the project and, thus, leads to an erroneous assessment of the benefit attributable to the project investment.

Sources of capital for rainwater harvesting

Sources of capital for investing in RWH projects are:

(i) Owner equity (savings and labour); and
(ii) Borrowed capital. This needs a well-written feasibility study, requires collateral and needs to be combined with owner equity (the equity ratio should have a high percent of owner contribution relative to the total cost of the project).

Questions normally asked when borrowing capital are: 'Should you borrow?', 'Will the borrower be able to repay the loan?', 'When to borrow?', and 'How much to borrow?'

In order to acquire capital, lenders will always require information, for example project costs and benefits, and a feasibility study, and they will always stipulate conditions, for example regular reporting according to the lender's requirements.

8.4 Case studies

Case study 1: Profitability of rainwater harvesting techniques in crop production, Tanzania

This case study was conducted in two sites, representing semiarid areas of Tanzania: the Western Pare Lowlands (WPLL) in the Mwanga and Same Districts in the northeast, and the Maswa District, in the Shinyanga region, south of Lake Victoria (Fig. 46).

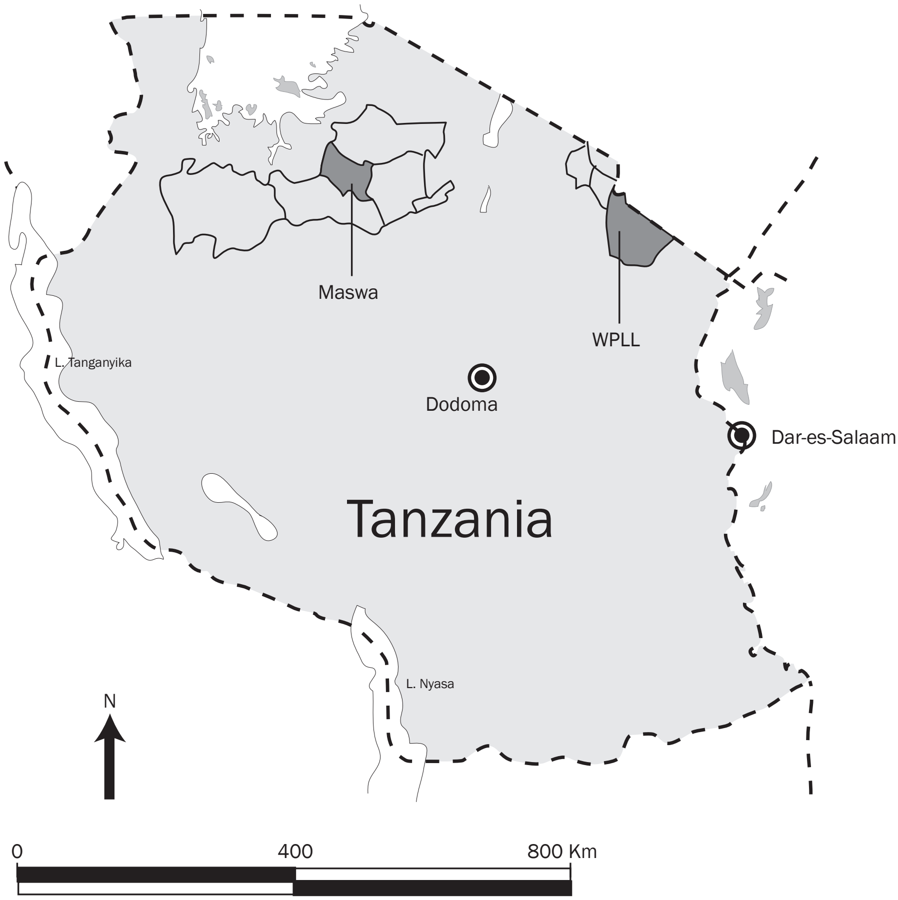

Figure 46: *Case study 1. Location of the rainwater-harvesting study area in Tanzania*

Production of maize (by ephemeral stream diversion), paddy rice (in bunded basins) and onions (in storage structures called *ndiva*) were evaluated using gross margins and investment analysis (B:C ratio, NPV and IRR).

Results

The results showed that RWH improved gross margins as well as returns to labour (Table 11). The gross margins and returns to labour obtained by onion farmers demonstrate the tremendous benefits of RWH. Where markets are available, RWH enables farmers to switch to high-value crops, with very significant improvements in incomes and, thus, in livelihoods. Maize production with RWH (diversion canals) had a positive NPV, a B:C greater than one and an IRR of 57% (Table 12). Similarly, paddy production with RWH had a positive NPV, a B:C ratio greater than one and an IRR of 31%. This case study demonstrated the potential for, and profitability of RWH, even under different price scenarios (Table 13). Thus, it is recommended that RWH should be a priority in Tanzania, particularly in semiarid areas.

Table 11: *Gross margins and returns to labour2 of rainwater harvesting (RWH) in maize, paddy and onion production, Western Pare Lowlands (WPLL) and Maswa District, Tanzania*

Enterprise		With RWH		Without RWH	
		Gross margin TShs/ha	Return to labour TShs/person days	Gross margin TShs/ha	Return to labour TShs/person day
	Head	126,496	3,997	N/A	N/A
	Middle	154,581	4,139	N/A	N/A
Maize	Tail	51,854	2,556	N/A	N/A
	Overall	121,069	3,713	-53,197	-26
Paddy		136,814	868	N/A	N/A
Onion		2,204,017	11,057	N/A	N/A

Table 12: *Investment analysis for rainwater harvesting in maize, paddy and onion production, Western Pare Lowlands (WPLL) and Maswa District, Tanzania*

Enterprise	NPV (10%) (TShs)	NPV (20%) (TShs)	B:C ratio	IRR (%)
Maize	379,669	202,460	1.6	57
Paddy	20,623	7,549	1.0	31
Onion	2,583,259	1,155,384	1.5	38

Table 13: *Sensitivity analysis for rainwater harvesting in maize production, Western Pare Lowlands (WPLL) and Maswa District, Tanzania*

Scenarios	Performance indicators			
	NPV (10%) (TShs)	NPV (20%) (TShs)	B:C ratio	IRR (%)
Basic scenario	379,669	202,460	1.6	57
20% increase in costs	241,419	103,906	1.3	37
20% decrease in product price	165,485	63,413	1.3	33

Case study 2: Economics of rainwater harvesting for crop enterprises in semiarid areas of East Africa

This case study presents an analysis of the economics of RWH in Tanzania. Researchers surveyed 120 households to obtain data on the performance of their enterprises over six years (1998–2003). The data was mainly based on recollection as few farmers kept detailed records.

Yield and inputs were monitored and measured on-farm over the 2002/2003 and 2003/2004 production seasons. The results were analyzed for four categories of RWH systems, differentiated by the size of catchments from which rainwater was collected and how water was concentrated and/or stored. The four categories were: micro-catchments, macro-catchments, macro-catchments linked to road drainage and micro- or macro-catchments with a storage pond.

Results show that RWH for production of paddy rice paid most, with returns to labour of more than US$12 per person-day invested. These returns are very high, because without RWH paddy production is not possible in the study area and rainfed sorghum realizes a return to labour of only US$3.7 per person day during average seasons. RWH systems designed to collect water from macro-catchments linked to road drainage performed best over the 2002/2003 and 2003/2004 production seasons.

Case study 3: Cost–benefit analysis of paddy and maize production in Dodoma, Tanzania[3]

Hombolo village in the Dodoma region of Tanzania (35°55'E and 5°55'S) is 850–875 m above sea level. This area consists of isolated hills, inselbergs and ridges, rising above peneplains. Soil and landscape form a catenary sequence with four components: hilltops, foot slopes, peneplains and river valley bottoms. Many farmers exploit runoff by growing high water-demand crops in valley bottoms. Fields in these areas are called *mashamba ya mbugani* (distant fields) and are mainly used to grow maize. Farmers value these areas because nutrients transported and deposited from upslope areas during seasonal flooding enrich fertility. Some farmers lead the nutrient-rich runoff and into bunded fields (*majaluba*) for growing paddy rice. In some villages, there is a high demand for such low-lying fertile areas and an active sale and rental market.

Cost–benefit analysis was used to compare the profitability of paddy rice grown in *majaluba* to the profitability of maize grown in distant fields. The financial net present value (NPV) criterion was used to compare the profitability of paddy and maize in smallholder agriculture.

The cost of construction of *majaluba* was amortized over a period of 10 years. Annual maintenance costs of 10% of the original labour cost were assumed. In the real world, farmers would make continuous modifications to the *majaluba*. In year one, the investment made was that involved in constructing the structure and the benefits were realized in the same year. Costs and prices used are constant 1994 market prices to take care of inflation in subsequent years.

In calculating the NPV, the opportunity cost of capital (discounting rate) was set at 10%. However, since interest rates offered by commercial banks at that time (1999) were about 24%, calculations applying the commercial rate were also made to indicate the alternative financial opportunity available to farmers.

Maize production does not require a substantial investment in land preparation. Simple gross margins could therefore have been used. However, because the aim is to compare the profitability of rainwater harvesting investments for paddy and maize, projections for maize need to cover a 10-year period. Table 14 shows cost–benefit projections for paddy rice grown in the *majaluba* system, while Table 14 shows the discounted NPV for paddy.

Table 14: *Costs and benefits for rainwater harvesting investment in paddy production in Dodoma, Tanzania*

Costs/benefits	Year					
	1	2	3	...	9	10
	TShs					
A. Costs						
Investment cost: 320 man-days @ TShs267/day	85,440	0	0	-do-	0	0
Land preparation 20 man-days @ TShs267/day	5,340	5,340	5,340	-do-	5,340	5,340
Maintenance cost (10% of labour cost)	0	8,544	8,544	-do-	8,544	8,544
Planting: 9 man-days @ TShs267/day	2,403	2,403	2,403	-do-	2,403	2,403
Weeding & thinning: 17 man-days @ TShs267/day	4,539	4,539	4,539	-do-	4,539	4,539
Harvesting, threshing and winnowing	16,020	16,020	16,020	-do-	16,020	16,020
Seed and fertilizer costs	2,857	2,857	2,857	-do-	2,857	2,857
Total costs (not discounted)	116,599	39,693	39,693	-do-	39,693	39,693
B. Benefits						
Selling paddy rice at TShs9,000/bag	64,800	64,800	64,800		64,800	64,800

Table 15: *Discounted net benefits for rainwater harvesting investment in paddy production in Dodoma, Tanzania*

Year	Benefits	Costs	Net benefits	Discounted	Net benefits
1	64,800.00	116,599.00	-51,799.00	-47,085.30	-41,750.00
2	64,800.00	39,693.00	25,107.00	20,738.40	16,319.60
3	64,800.00	39,693.00	25,107.00	18,855.40	13,156.10
4	64,800.00	39,693.00	25,107.00	17,148.10	10,620.31
5	64,800.00	39,693.00	25,107.00	15,591.40	8,561.50
6	64,800.00	39,693.00	25,107.00	14,160.30	6,904.40
7	64,800.00	39,693.00	25,107.00	12,879.90	5,573.80
8	64,800.00	39,693.00	25,107.00	11,725.00	4,494.20
9	64,800.00	39,693.00	25,107.00	10,645.40	3,615.40
10	64,800.00	39,693.00	25,107.00	9,691.30	2,912.40
				84,349.90	30,407.70

Calculation of NPV for maize grown in distant fields is shown in Table 16. Since the same costs and benefits occur in each year, annuity factors at both 10% and 24% were used to discount the net benefits.

From the results, it can be concluded that both paddy and maize production are profitable since they have positive NPVs. For both discount rates (10% and 24%), however, the returns from paddy production were higher than those from maize. Using the decision criterion of high NPV (and other available information), the planner is in a position to make recommendations on the above scenarios. Based on the analysis and assumptions made, the planner is expected to choose the alternative with the highest NPV, in this case, paddy rice production using the *majaluba* system.

Table 16: *Cost–benefit analysis of rainwater harvesting investment in maize production in Dodoma, Tanzania*

Costs and benefits	1	2	3	9	10
			TShs		
Costs					
Land preparation 1 man-day	267	267	-do-	267	267
Planting: 2 man-days + TShs1,000 for communal labour	1,534	1,534	-do-	1,534	1,534
Weeding: 25 man-days + TShs7,300 for communal labour	13,975	13,975	-do-	13,975	13,975
Maintenance cost (10% of labour cost)	4,319	4,319	-do-	4,319	4,319
Harvesting and threshing: 7 man-days + TShs2,450 for communal labour					
Transport	3,000	3,000	-do-	3,000	3,000
Total costs of production	23,095	23,095	-do- -	23,095	23,095
Benefits					
Selling maize 4 bags/acre @ TShs7,500/bag	30,000	30,000	-do-	30,000	30,000
Net benefits (benefits – costs)	6.905	6.905	-do-	6.905	6.905
NPV at 10% (annuity factor t.145)1					

8.5 Conclusions and recommendations

This chapter has shown that the principles of economic theory can be applied in analysing the economics of RWH as well as in evaluating RWH projects. The chapter has also shown that water/rainwater for crop production can be used as an input in production and that average and marginal productivities of water can be evaluated for specific crops.

In the three case studies, RWH practices for crop production were found to be profitable. Profitability becomes more apparent when producers of crops are linked to markets.

Based on the case studies, it is recommended that economic methods should be used to analyse and evaluate RWH projects. Both ex-ante and ex-post evaluation can be done. For investments in RWH to have an impact on poverty reduction, increased linkages to profitable markets are critical as the results show that increasing cash income is a leading priority of farmers.

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Chapter 9

Extension Methodology

9.1 Introduction

Extension can be defined as the conscious communication of information to help people form sound opinions and make good decisions.It can also be defined as all organized and coherent non-formal education activities by which an agency—on the basis of clients' needs, problems and development perceptions—attempts to impart knowledge, change attitudes and behaviour or improve skills to raise agricultural production and/or improve standards of living.

9.2 Extension strategy

The extension strategy can be defined as an organized and coherent combination of extension methods and activities designed and implemented to make extension effective at a certain time and in a certain area and situation.

Since World War II, extension has been constantly re-invented and new strategies, methods and activities have been continually developed to make it more effective as a tool for development. Six characteristic extension strategies have been developed since World War II. These are:

- The scheme strategy
- The commodity strategy
- The transfer of technology strategy
- The target group strategy
- The community management based strategy
- The knowledge and information systems strategy.

The scheme strategy

The scheme strategy in extension aims to reinforce the rules and regulations of, for example plantations, collective farms, supervised out-grower schemes, and irrigation and resettlement schemes. In such schemes, it is usually the management that has control over most of the production factors. Farmers implement decisions made by management and extension focuses on instructing and/or convincing farmers to follow the rules set by management. In these cases, extension activities often include providing technical information to farmers or tenants.

A well-managed scheme, geared towards the well-being of tenants or farmers, and aiming for participatory management, can be an excellent instrument for development and can create employment for a large number of people. This is because management controls the whole development 'mix', which includes extension as well as input supplies, water regulation, credit and marketing.

However, in cases where the farmers/tenants perceive that the management is extracting produce and wealth from the enterprise for their own benefit, conflicts between tenants/farmers and the scheme management result. In these cases, management may respond in an authoritarian manner and the farmers/tenants may resort to sabotaging the scheme's rules and regulations—using inputs on fields other than those they were intended for, not repaying loans, working on their own fields rather than on the scheme fields, diverting irrigation water to their own fields—resulting in low production.

The commodity strategy

The commodity extension strategy is geared towards the production of one specific crop (commodity) and provides all elements of the mix necessary to grow and market it. The strategy is often managed by a large corporation, society or board (e.g. the Kenya Tea Development Authority) which has either monopolized the market or operates within a compulsory cropping system. Such agencies often have a separate extension unit to disseminate technical knowledge. In this strategy, each individual farmer has direct contact with the corporation, society or board and is dependent upon that agency to supply inputs and planting materials, and to market produce.

Most commodity organizations are selective when involving farmers in their operations and have the tendency to choose the best farmers with the best land. This leads to a skewed distribution of the benefits in a farming community.

The transfer of technology strategy

This strategy, also called the Technical Change Strategy, is the most widely known and practiced of all strategies. The objective is to transfer information about improved farming practices from researchers to farmers and to demonstrate to farmers how they can improve production by adopting recommended practices.

This strategy diffuses technical information (ideally) indiscriminately within the community. Farmers are left free to decide whether or not they want to receive the information or to try, adopt or reject the recommended practice. Extension workers often introduce recommended practices to innovative or progressive farmers (often used as demonstration farmers) in the hope that autonomous diffusion processes will spread information rapidly through the community and that the practices will be quickly adopted by the majority of farmers (the trickle-down effect).

For the transfer of technology strategy to be successful, a number of conditions have to be met. The recommended practices should be technologically sound and should work under local on-farm conditions. In many instances this has not been the case because the research workers who originally formulated the recommendations did not appreciate that the controlled conditions in their experimental plots differed substantially from those in farmers' fields. Many new crop varieties that performed well in experimental plots failed miserably when planted outside the research station.

The production objectives of the extension strategy should align with those of farmers. Much agricultural research was based on the (often implicit) assumption that farmers in the tropics had the same production objectives as farmers in industrialized countries—produce as much as you can and in the process take some risks to make a good profit (profit maximization). In many rural societies in Africa, Asia and Latin America, this is not the case, certainly not in smallholder communities. In these areas, farmers' main production objective is to minimize risks and to make sure that a household's food harvest is enough to last until the next season. These farmers have no use for improved varieties or other recommended practices that make their crops more susceptible to attacks by insects and pests, more dependent upon annual rains or a regular supply of irrigation water, or that need large quantities of fertilizers and other agricultural chemicals.

A transfer of technology strategy should recognize that most farming communities in developing countries are heterogeneous in nature. The progressive or innovative farmers often belong to a small upper class of economically and socially influential farmers—these have large farms, are more educated, have easy access to credit, input supplies and markets and, hence, are in a position to adopt the recommended practices. On the other hand, the majority of smallholder farmers may not be in a position to adopt the recommended practices. Extension workers' advice will be rejected as long as they recommend practices that do not match farmers' production objectives, needs and development opportunities. Thus, the transfer of technology strategy as a means to help alleviate poverty is unsuitable if used indiscriminately in heterogeneous communities. It may exacerbate inequities where innovations are introduced to progressive and innovative farmers and expected to trickle down. In most cases this does not happen and has actually led to innovative farmers expanding their farms by buying out small farmers or even pushing them out to become squatters. Technical innovations introduced by extension workers have often been either too risky or too expensive for resource-poor farmers. An example of such a 'transfer of technology' strategy is the World Bank's Training and Visit System for agricultural extension.

The target group strategy

The target group extension strategy works on the assumption that village populations are hardly ever homogeneous and can, therefore, be divided into subgroups (target groups or target categories) that have their own development needs, preferences and potential. After establishing the main subgroups and how they differ from each other, one or two of these subgroups are selected, and extension programs are designed to disseminate information specifically to these target groups.

The target group strategy takes advantage of the autonomous diffusion of innovations, the natural way in which new ideas and practices spread through a community over time and are adopted by some of its members and rejected by others. Once an extension agency or a development organization has selected innovations that match the situation of target group members, there is no harm in letting horizontal diffusion processes have their way.

The community-based management strategy

This works on the assumption that rural communities can, and in fact should, carry the main responsibility for the development of their area. Government and non-government personnel may assist and facilitate the process, but are no longer responsible for implementation. This strategy uses participatory extension and communication methods. The emphasis is on increasing the ability of the community or group to solve problems and take collective decisions. The recipients of extension are participants with a common problem which can only be solved through a higher degree of organization and platform building. This strategy is particularly appropriate for sustainable management of natural resources.It is desirable for community members to participate in decisions regarding the extension program for the following reasons:(i) They have information which is crucial for planning successful extension, including their goals, situation, and knowledge, experiences with technologies and with extension, and of the social structure of the community.(ii) They will be motivated to cooperate in the extension program if they share responsibility for it.(iii) In a democratic society it is generally accepted that people have the right to participate in decisions about the goals they hope to achieve.(iv) Many development objectives, such as rainwater harvesting, preventing soil erosion, and sustainable farming systems, can no longer be implemented by individuals. Participation of the target group in collective decisions is required.However, this approach faces several challenges because individuals or small groups are part of larger groups and personal interests often interfere with collective interests.

Chapter 10

Sustainable use of water resources

10.1 Introduction

Sustainable development is a leading philosophy that, on the one hand, allows the world to develop its resources and, on the other hand, to preserve non-renewable and finite resources while guaranteeing adequate living conditions for future generations.

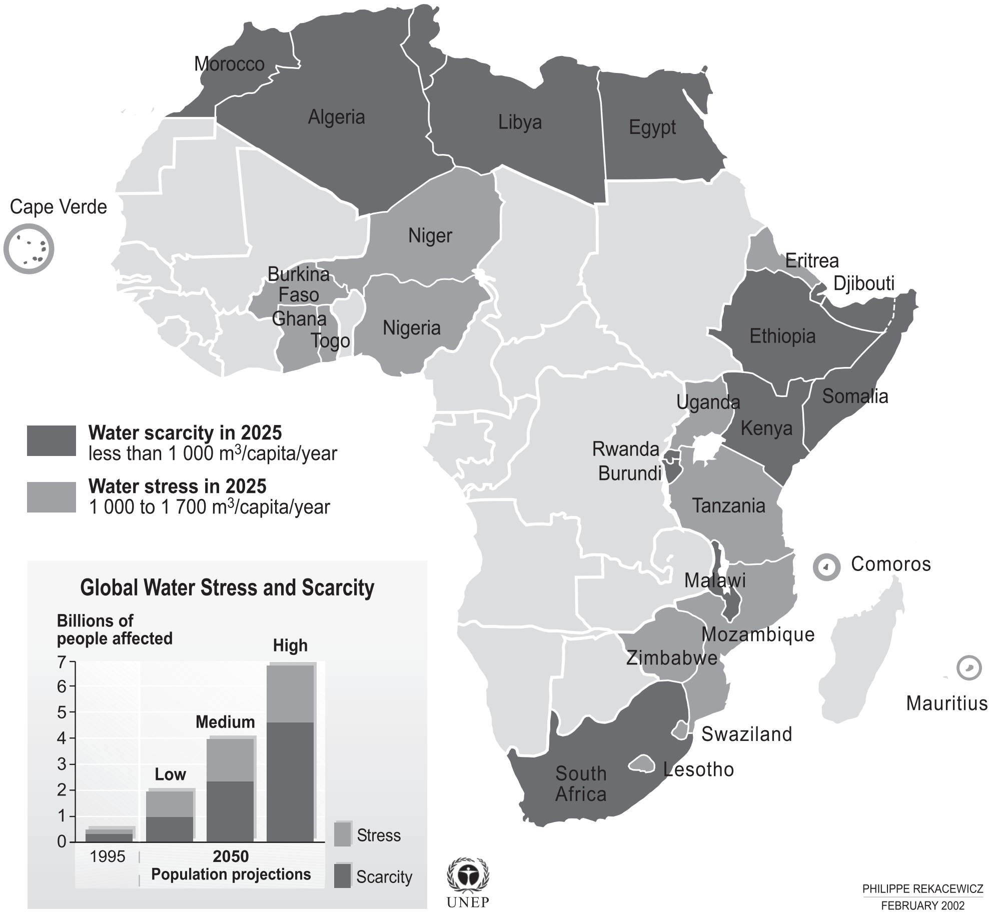
Definition of sustainable development

- The ability of the present generation to utilize its natural resources without putting at risk the ability of future generations to do likewise.
- The efficient use of natural resources for economic and social development while maintaining the resource base and environmental carrying capacity for coming generations.

This resource base should be widely interpreted to contain, besides natural resources:

- Knowledge
- Infrastructure
- Technology
- Human resources.

In many parts of the world, including Africa (Fig. 47), freshwater resources are scarce and, to a large extent, finite. Although surface water may be considered a renewable resource, it constitutes only 0.3% of all terrestrial fresh water resources (Fig. 48). The vast majority of the earth's freshwater is held in icecaps (68.7%) and groundwater (30.1%) which—at a human scale—is virtually unrenewable.



Source: United Nations Economic Commission for Africa (UNECA), Addis Ababa; Global Environment Outlook 2000 (GEO), UNEP, Earthscan, London, 1999; Population Action International.

Figure 47: *Freshwater stress and scarcity in Africa by 2025*

Consequently, future supplies of water will be jeopardized by overexploitation (mining) of water resources or by destroying resources for future use (e.g. pollution). Aspects of sustainability of water resources hence include the following, which are each discussed in turn below:

1. Physical sustainability
2. Technical sustainability
3. Financial sustainability
4. Social sustainability
5. Economic sustainability
6. Institutional sustainability
7. Environmental sustainability.

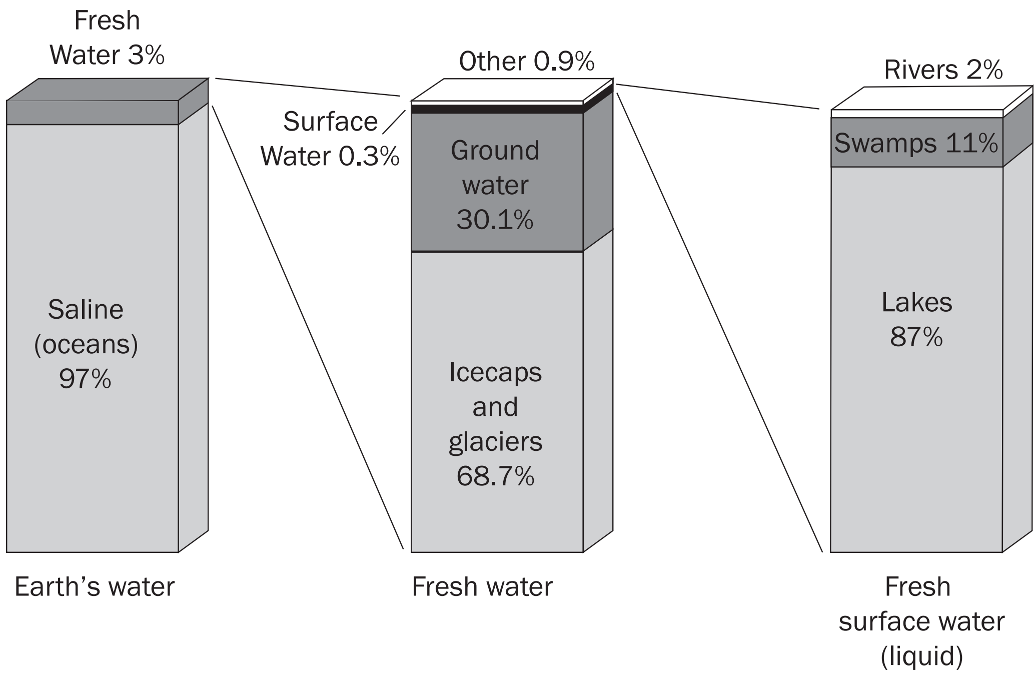


Figure 48: *Distribution of the earth's water*

10.2 Conditions for sustainability

Using water resources sustainably requires attention to all the aspects of sustainability listed above.

Physical sustainability

This considers water and nutrient cycles. In the nutrient cycle, depletion of nutrients leads to loss of soil fertility and soil water capacity, and accumulation leads to eutrophication and pollution. 'Closing' the nutrient cycle means restoring equilibria at the appropriate temporal and spatial scales. Globally, because time scales over which cycles close are large—billions of years—cycles are not temporally and spatially sustainable in human time scales. The smaller the scale of closure of the cycles, the more resources are conserved and recycled, and the more efficient the system. Water cycles only close if safe yields are not exceeded, or if extraction of groundwater is compensated by (artificial) recharge. Cycles can be closed at rural, urban, river basin and global scales. At the rural and river basin scales, cycles can be closed by conserving soil and water, retaining floods, controlling pollution, using wetlands wisely, preventing excess drainage, and recycling nutrients and organic waste. Economic efficiency at an appropriate scale encompasses social and environmental costs and benefits to society, for example opportunity costs and externalities.

Economic sustainability

Economic sustainability refers to the sustainability of economic development or welfare and production. It relates to the efficiency of the system. If all societal costs and benefits are properly accounted for, and cycles are closed, then economic sustainability implies a reduction the scale of closure of the cycles. The closing of cycles with respect to physical sustainability implies that resources (e.g. nutrients) are transported back to where they came from. Examples of short cycles include the following: water conservation (making optimum use of water where it falls, rather than letting it drain off and then pumping it up again for irrigation or water supply; conservation agriculture is thus economically sustainable); nutrient conservation to minimize loss of fertility; water recycling and conversion of waste into bio-gas. Economic sustainability is facilitated by an enlargement of scale through the virtual water trade, especially in countries without the resources to produce products that require intensive use of land and water. Such countries can use their financial resources to import these products (and thus land and water in a virtual form).

Eventually, after billions of years, all cycles close, and balances are restored. But because the time scale over which cycles close is large, cycles are not sustainable at a temporal and spatial human scale. The smaller the scale of closure of cycles, the more resources are conserved and recycled and the more efficient the system is. Food and nutrient cycles should be as short as possible. Water cycles only close if safe yields are not exceeded, or if groundwater withdrawals are compensated with artificial recharge.

The closing of cycles should be realized at different scales:

- The rural scale—water conservation, nutrient and soil conservation, prevention of excess drainage and recycling of nutrients and organic matter.
- The urban scale—both in towns and cities, recycling water, nutrients and waste. In mega-cities, systems should be broken down into small manageable units (neighbourhoods, compounds, building complexes).
- The river-basin scale—soil and water conservation in the upper catchment, prevention of runoff and unnecessary drainage, flood retention, pollution control, and wise use of wetlands.
- The global scale—integration of water, nutrient and basic resource cycles. The paradigm of economic sustainability is therefore 'small is beautiful' in relation to the spatial scale of sustainable cycles.

Technical sustainability

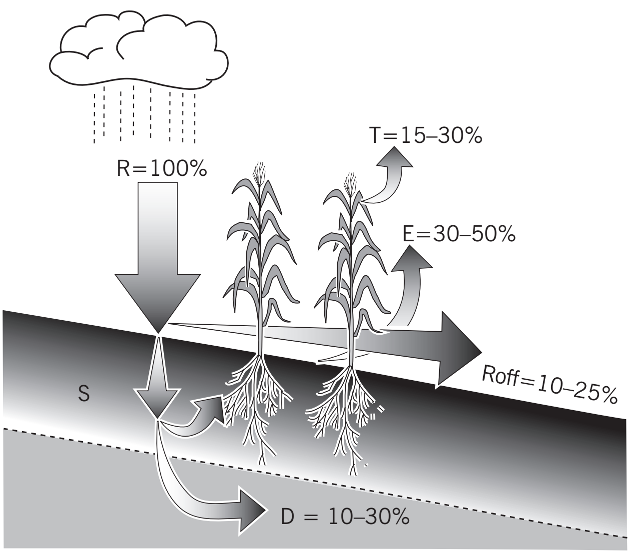
This refers to the balancing of water supply and demand with a view to achieving maximum agricultural productivity without jeopardizing the environment—neither over-exploitation nor under-supply. In order to manage supply and demand, an inventory of all households/farms should be compiled (Fig. 49). The data from such an inventory is useful in assessing the domestic, agricultural and environmental water demands. An assessment of water demand helps in planning integrated water resources management strategies to meet the water needs of a given locality.

Household name	Family size	Size of homestead	Inventory of buildings (Roof sizes)			Farm inventory						Surface Water resources inventory			
			House 1	House 2	House 3	Farm 1				Livestock		Pond	UG tank	Well	Spring
		(m^2)	(m^2)	(m^2)	(m^2)	sizes (m^2)	RWH potential	Crop	CWR	Spp	Water demand	(m^3)	(m^3)	(m^3)	(m^3)

Figure 49: *Data collection form to assess water demand*

A hydrological survey of surface and groundwater resources should be carried out periodically to determine existing water supplies. A water resources map should then be produced using GPS/GIS (or a sketch developed from a topographic map). The map should show the hydrological units at catchment, watershed and basin scale, as well as existing water resources.

The potential water supply should then be computed and incorporated into the hydrological map. Agricultural water allocations that would not jeopardize the environment should be determined. The allocations should conform to the partitioning shown in Fig. 50. The resulting hydrological map will be the basis of the implementation plan.



Source: Rockström J. 2003

Figure 50: *Rainwater partitioning*

Crops and livestock need adequate supplies of fresh water, particularly at critical stages of development. In the case of crops, the soil moisture regime can be augmented by three conservation farming methods: in situ rainwater harvesting, crop rotation and mulching. Should these measures be insufficient during dry spells, then runoff water harvested and stored in reservoirs such as ponds, tanks and earth dams, and water abstracted from perennial rivers or groundwater aquifers, can be applied as supplementary or total irrigation. The amount of water withdrawn from underground spherical tanks (Fig. 51) for supplementary irrigation can be determined using the formula below (Oduor, 2003):

$$V = \frac{1}{3}\pi b^2 (3R - b)$$

Where

V = volume of water supplied for supplementary irrigation (m^3)

b = depth of water in the tank (m) and

R = tank radius (m)

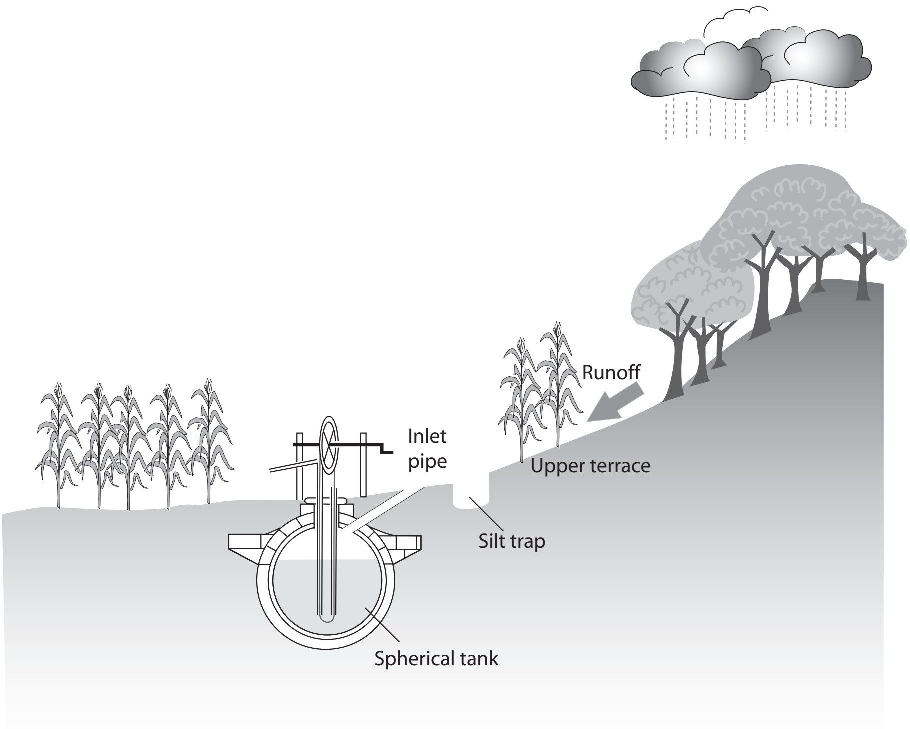


Figure 51: *Schematic representation of a spherical tank*

Sustainability of water resources based on multi-criteria analysis (MCA)

The choice of an appropriate reservoir, as a source of supply of supplementary irrigation water, contributes to technical sustainability. A number of criteria have to be considered in order to make the right decision. These include the cost per unit volume, reservoir capacity, the possibility of expanding or cascading the capacity, the distribution of hydraulic forces, the adoptability of the technology, seepage and evaporation losses, operation and maintenance, the risk of siltation and organizational aspects (Oduor, 2003). Analysis of these factors for the various options requires the use of multi-criteria analysis (MCA). MCA refers to a set of techniques that aim to rank alternative strategies according to a chosen set of criteria . MCA also serves to classify, analyze, arrange and take an inventory of available information concerning alternative strategies in resource planning. Performance values (scores) are entered on 'scorecards' and expressed in different units. These are later standardized using the formula below:

$$STD_{KJ} = \frac{CT_{KJ} - Worst_{(1.......N),J}}{Best_{(1.....N),J} - Worst_{(1.....N),J}}$$

Where

Where STD_{KJ} = *Standardized score*

CT_{KJ} = *ctual score*

$Worst_{(1...N),J}$ = *Worst score*

$Best_{(1...N),J}$ = *Best score*

An example of a scorecard for multi-criteria analysis before and after standardization

This example is based on research conducted in Machakos, Kenya, by Oduor (2003), on four types of reservoir: sausage tank, spherical tank, plastic-lined tank and small earth dam. Actual values for the following criteria were determined for each reservoir: capital cost, storage capacity, excavation depth, cost per unit volume of water, number of reservoir units adopted, and evaporation rates. The remaining criteria were described as either 'low' or 'high' and were as follows: possibility of increasing reservoir capacity, distribution of forces, seepage losses, organizational aspects, operation and maintenance, and risk of siltation.

Since excavation for the construction of sausage tanks is lateral rather than vertical, as for the other three types of reservoir, the possibility of making them longer, and hence increasing their capacity, is high. Distribution of forces is also considered more uniform and, hence best in circular or spherical structures, such as the sausage and spherical tanks, compared to cube-shaped plastic-lined tanks or unevenly shaped earth dams. Since the smaller structures such as sausage, spherical and plastic-lined tanks are individually owned, they are easy to manage and require few organizational skills. Finally, unless holes or cracks have developed because the reservoir has dried out and been exposed to intense sunlight or has been damaged by burrowing animals, there is no seepage from the smaller structures. The risk of siltation is also less in smaller reservoirs as it is easier to install silt traps. Tables 16 and 17 below show scorecards based on MCA before and after standardization.

Table 17: *Multi-criteria analysis scorecard before standardization*

Criteria	Unit	Technological option				Score	
		Sausage	Spherical	Plastic lined	Earth dam	Best	Worst
Capital cost	US $	380	192	495	11500	192	11500
Capacity	m3	17.5	15	150	9000	9000	15
Unit cost	US$/m3	21.7	12.8	3.3	1.3	1.3	21.7
Excavation depth	m3	1.5	3	3	1.5	1.5	3
Possibility of increasing capacity	Descriptive	high	low	low	low	high	low
Evaporation	mm	0	0	1800	1800	0	1800
Seepage	Descriptive	low	low	low	high	low	high
Adaptability	no.	20	35	5	1	35	1
Organizational aspects	Descriptive	low	low	low	high	low	high
O & M	Descriptive	low	low	low	high	low	high
Siltation risk	Descriptive	low	low	low	high	low	high
Distribution forces	Descriptive	Uniform	Uniform	Poor	Poor	Uniform	Poor

Table 18: *Multi-criteria analysis scorecard after standardization*

Criteria	Technological option			
	Sausage	Spherical	Plastic lined	Earth dam
Capital cost	0.98	1.00	0.97	0.00
Capacity	0.00	0.00	0.00	1.00
Unit cost	0.00	0.40	0.90	1.00
Excavation depth	1.50	3.00	3.00	1.50
Possibility of increasing capacity	1.00	0.00	0.00	0.00
Evaporation	1.00	1.00	0.00	0.00
Seepage	1	1	1	0
Adaptability	0.60	1	0.1	0
Organizational aspects	1	1	1	0
O & M	1	1	1	0
Siltation risk	1	1	1	0
Distribution forces	1	1	0	0
Total Scores	10.08	11.40	8.97	3.50

Financial sustainability

Financial sustainability refers to cost recovery. Since the capital required for water infrastructure, such as tanks or ponds, for individual use is rather costly, farmers often organize themselves into groups. Here, individuals are required to contribute labour and cash on rotational basis for the construction of a tank for each member. The group members, often women, prefer the quick benefits gained by individual ownership of tanks. The group organizes or solicits for table banking, which is a micro-credit system. Table banking is a pool where rotational funding can be effected. If the investments are too high, then the group seeks part funding from external support agencies, such as micro-finance banks, NGOs or the government.

A capital cost recovery formula or annuity factor to solve capitalization plans based on the French amortization system is presented in the formula below (De Heer, 2002):

$$= \frac{i(1+i)^n}{(1+i)^n - 1} P$$

Where

= *nnuity factor (contribution) on monthly basis*

P = *Capital cost*

i = *Interest rate for payment*

n = *Payment period*

The monthly contributions per member, worked out from the annuity factor, are what constitute the capital recovery and, hence, financial sustainability. Tables 18 and 19 below show examples of the annuity factor, and evolution protocols for capitalization of spherical and sausage tanks for a women's group in Machakos District (Oduor, 2003).

Example

The mango women's group has ten members. They operate a merry-go-round system that enables group members to share funds money and labour.

Table 19: *Annuity protocol for a table banking micro-credit system*

Item	Symbol	Formula	Value
Present value	P		15000
Monthly interest rate	i	(15%) *P)/12	0.0125
Payment period	n	Determined	6
Capital recovery for group	A	((i(1+i)^n)/((1+i)^n-1))*P	2610.507
Recovery + interest	Ri	(A+i)	2798.01
Group members	Gm	Determined	15
Monthly contribution/member	mm	(A+(P&i)/Gm	186.53
Monthly contribution/group	mG	(mm*Gm)	2798.01
Total contributions for the project	TG	(mG*n)	16788.04
Profit accrued from interest	Pi	(TG-P)	1788.04

Source: Oduor (2003)

The total cost of a given infrastructure, P, is determined by the water resources engineer. The group can then decide on the interest, i, and the period, n, within which they are comfortable making payments.

Table 20: *Evolution protocol for a table banking micro-credit system*

Cell	A	B		C	D		E
1	n	Payment	Interest formula	Interest	Principal	Balance formula	Balance
2	0						15000
3	1	2610.51	(((15%)*P/12))*E2	187.50	B3-C3	E2-D3	12576.99
4	2	2610.51	(((15%)*P/12))*E3	157.21	B4-C4	E3-D4	10123.69
5	3	2610.51	(((15%)*P/12))*E4	126.55	B5-C5	E4-D5	7639.73
6	4	2610.51	(((15%)*P/12))*E5	95.50	B6-C6	E5-D6	5124.72
7	5	2610.51	(((15%)*P/12))*E6	64.06	B7-C7	E6-D7	2578.26
8	6	2610.51	(((15%)*P/12))*E7	32.23	B8-C8	E7-D8	0.0
	Total	15663.06	SUM (C3:C8)	663.05	SUM(N3-N8)		

Adapted from Oduor (2003)

Social sustainability

Social sustainability refers to the willingness and ability of the community to contribute in cash or kind, to the stability of the population and stability of demand. When the contribution per member of a group is as low as KShs186.53 (US$2.6) for six months, as demonstrated in the annuity protocol above, members do not find it difficult to pay and, hence, are quite willing to contribute. Groups consisting of members who are able and willing to pay are more cohesive. Cohesive groups attract others seeking to invest in such ventures. The overall result is increased adoption.

Institutional sustainability

Institutional sustainability refers to the capacity to plan, manage and operate a system. It requires a well-trained and multi-disciplinary pool of personnel that has the ability to cope with present and future challenges. There should be an institutional framework that ensures that partnerships and collaboration are fully exploited to avoid duplication of effort and waste of resources.

Environmental sustainability

Environmental sustainability refers to the objective of avoiding long-term negative and irreversible effects. Environmental management authorities are well-placed to formulate policies and impose stringent laws to ensure that users do not pollute water resources that are used by their neighbours or that will be used by future generations.

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Chapter **11**

Gender issues in rainwater management

The last decade has seen increased interest in gender issues in all rural development projects. In smallholder irrigated agriculture, women provide 60–90% of the intensive labour in the fields but do not accrue proportional benefits.

11.1 Issues that marginalize women

Many issues marginalize women and hinder their inclusion in development. Some of these are discussed below.

Workloads
Rural women work both in the home and on the farm. Their workloads are particularly heavy where agricultural production is labour intensive. A female adult works an average of 15 hours per day while a male adult works only 7–8 hours a day. Often, the women lack access to the benefits of their labour. This is a disincentive and is a labour constraint in irrigated production.

Education and literacy
In education, women in rural areas lag far behind men. Low literacy rates of 20–30% are common among women involved in irrigation schemes. Many girls drop out of education due to early pregnancy or marriage. Parents often prefer to educate sons. These issues hinder the participation of women in projects, their access to information about agronomy, markets and credit, and have marginalized women into low-technology low-income-generating activities.

Extension
Women provide up to 80% of agricultural labour in Sub-Saharan Africa but, to date, only 7% of extension workers in agricultural projects have contacted these rural women. The problems in many irrigation projects may thus be attributed to the fact that extension messages reach very few women and, thus, very few practitioners.
Credit

Women have great difficulties in obtaining credit. Banks do not see them as creditworthy. To be creditworthy in the eyes of a bank, ownership of land is required, yet land is almost always owned by men and passes to sons. In the few cases where women are extended credit, repayment rates are high.

Benefits, rights and obligations

Rights to land usually rest with males and are passed on to males, whereas obligations to feed children, fetch water, gather fuel and to work on their husbands' land normally rest with women. Formalizing tenancy arrangements with women can enhance their status.

Participation in water resources decisions and policies

Few women participate in community meetings and water-user groups. Fewer women participate in Government policy-making processes. Most rural women are not involved in planning and have few opportunities to express their interests. The lack of empirical data on the role of women in many irrigation schemes denies women the chance to argue cogently for more inclusion in decision-making processes. Encouraging men and women to share responsibilities, decision-making and planning should improve development and reap benefits for all.

11.2 Gender disparities in irrigated agriculture

Because gender disparities in irrigated agriculture are complex, the impacts on production, or on the levels of poverty experienced by different genders, are often difficult to identify. Gender disparities are normally evident in the following.

Access to resources and value of irrigated agriculture

Men and women place different values on irrigated agriculture. Land tenure arrangements usually favour men. Women landholders are often widows whose access to other resources is limited. Access to water is linked to land rights, but rights to land do not necessarily confer access to water. The domestic obligations of women may restrict their access to water at certain times of the day, for example where there are social and economic constraints to access to distribution points. As mentioned above, many banks do not favour women borrowers. Women also have difficulties in physical access to lending institutions, which are often in distant towns.

Agricultural processes

Women are well aware of the importance of land preparation, weeding, and the benefits of deep ploughing but find that implementing these practices is very wearisome.*Marketing aspects*Accessibility to markets, both in terms of cost and transport, poses greater difficulties for women compared to men. Although marketing agricultural produce is a common problem for both men and women, women tend to find it more difficult. Where vehicles are available, men tend to have better access, whereas women have to carry produce themselves and travel on foot or wait for infrequent buses. Women also have more problems finding markets than men do. This is partly because they tend to sell only small quantities of vegetables, for which no contracts are sought, and also because it is more difficult socially for them to travel away from home.

Agricultural tools

Agricultural tools are often inappropriate for women. The tools they use may be lighter in weight than those used by men, and easier to use, but may not be so effective and efficient.

Knowledge of machinery

Women have little knowledge and interest in irrigation equipment, such as pumps. When equipment breaks down, they may not be able to fix it and so resort to manual methods, such as irrigation with a watering can, which as well as being very tiring and time consuming, are damaging to their health.

Labour

The division of labour in irrigated agriculture is not proportional. Often women do more than half the work but have less access than men to resources and support services. Women do all the levelling work in making basins, yet levelling is the most difficult activity in basin irrigation.

Decision making

Women are often not involved in decision making, even about decisions which will affect them.

Time scheduling

The importance of irrigation scheduling is paramount, yet training programs on water delivery, information sessions and even meetings, are usually scheduled for times when women may not be able to attend. Hence, women miss out on important information.

Design of equipment

The design of equipment may pose risks to women's health, for example low-lift pumps may endanger their backs and treadle pumps their knees.

Crop preferences

Men prefer to grow cash crops while women prefer to grow food crops. Common irrigated agriculture technologies, such as long furrows, may be more suitable for cash crops than food crops. Women may thus feel out of place.

Training

Women are often not considered as targets for organized training and they may not even be available to attend due to workloads at home and on the farm.

Access to information

Women may not have had the chance of going to school and, hence, may be illiterate and unable to read information provided.

Financial issues

Women lack funds to start clubs which would enable them to borrow money to increase their productivity. The small amounts of food crops that they grow provide little income. This income basically goes to feed the family, as opposed to income from cash crops that goes to the men.

11.3 Gender-related irrigation design and management factors

Gender-related irrigation design and management factors are summarized in Table 21.

Table 21: *Gender-related irrigation design and management factors*

Issue	Gender perspective
Scheme layout	An unreliable water supply may increase marginalization of women. Women may not be interested in irrigation equipment, able to afford it or operate it.
Land preparation	Good soils need deep ploughing to be productive. Deep ploughing requires appropriate equipment, such as tractors. Men have priority over women in accessing such equipment. If such equipment is not available and tilling has to be done with hand hoes, this takes women's strength, energy and time.
Water distribution	Long furrows, which reduce versatility, predominate: these appear to favour cash crop production, which is mainly an activity of men, rather than small areas of vegetables, which tend to be a priority for women. The lack of water also adversely affects scheduling and exacerbates women's problems, as they must still meet their domestic commitments.
Pumps	Women are not included in discussions and decisions on maintenance costs, such as for repairing weirs or replacing pumps. Hence they have no opportunity to comment on their preferred options or the implications for their livelihoods.
Marketing	Women should be granted as many opportunities and offered as many contracts to sell their produce as men.
Finance	As women have less cash than men to purchase inputs, they are trapped in a cycle of poor yields and low incomes. Women traditionally have less access to credit than men and also lack collateral because of land tenure systems which favour men. These financial issues reduce women's opportunities.
Health and environment	Women may have poor access to distant health centres. Rivers may be prone to flooding and inhibit access. Such factors demand more of women's time than of men's, especially travelling to health centres, which men rarely do.

Chapter 12

Policy and legislation

For a long time, government policies did not acknowledge or consider rainwater harvesting (RWH). Although some line ministries recognized and promoted RWH, it was usually as part of other programs, such as soil and water conservation (S&WC). Government departments, for example agriculture, water, environment and natural resources departments, often initiated RWH programs, either directly or indirectly, but without consulting each other, resulting in uncoordinated and duplicated efforts.

In as much as irrigation has been paid adequate attention by governments, it has proved costly and uneconomic (particularly in rural areas), as is evident by the many large-scale irrigation schemes that have stalled. In addition, governments need to realize that surface water and groundwater resources, such as lakes, rivers and ponds, face the twin challenges of overexploitation and pollution, and that there is a need to harvest and conserve rainwater where it falls.

Policies that would be required to secure ecosystem goods and services include:

- A system for monitoring water allocation for all uses, including for environmental flows and protection of biodiversity;
- Design of economic incentives and regulatory arrangements for allocation and use(r) rights;
- Systems for valuing water, including social, economic and ecological values; and
- Education programs to improve understanding of the ecological implications of changes in the quantity and quality of water flow.

12.1 Review of Kenya Government policy documents

Policy is the set of decisions made at the highest political level in a country, usually after dialogue and consultation, which determine what, and how, things will be done in any given sector. Kenyan policy on various sectors is captured in sessional papers, development plans and acts of parliament. This section reviews pre-independence to post-independence policy documents that deal with water, agriculture and food security to highlight Kenyan Government views on RWH and food production.

Pre-independence

Colony of Kenya Water Ordinance No. 56 of 1951 (Colony of Kenya, 1951)

This ordinance made provision for the conservation, control, apportionment and use of water resources in the colony. Cap. 100 section 12 (1) stated that the member of the executive council of the colony responsible for agriculture and natural resources had, on the recommendation of the water resource authority, the power to construct and maintain upon any land, such works as he may deem necessary or desirable for any of the following purposes:

- protection of the source or the course of any body of water;
- disposal or control of flood water; and
- conservation of water.

The water ordinance, the supreme policy on water at the time, may have implied, but did not contain any concrete statement on RWH. Even the water ordinance of 1960, an amendment of the 1951 ordinance, did not include anything on RWH.

Colony and protectorate of Kenya: A plan to intensify the development of African agriculture in Kenya (Colony and Protectorate of Kenya, 1955)

This government document recognized that collecting rainwater from roof catchments might be one means of developing water supplies "where rainfall was deemed to be good". This statement presumably referred to RWH for domestic use. The document indicated an immediate need to set up a strong rural water and irrigation department, thus recognizing the importance of irrigation for intensifying agricultural production.

Post-independence

National development plans 1966–1983

National Development Plans (NDPs) are statutory policy documents that outline the Government's medium-term development policies and strategies. The first five-year NDP, issued in 1966, made no mention of RWH, although irrigation was mentioned in passing. The second NDP emphasized irrigation with river water. The third NDP (1974–1978) included plans to construct catchment dams to conserve surface water through the dry season. By the fourth NDP (1979–1983), RWH was beginning to be recognized as a way to conserve water and facilitate agricultural production, and the Plan specifically included construction of dams to conserve "*rainwater and surface runoff*".

Sessional paper no. 1 of 1981, on national food policy

To date, this is the only sessional paper on food policy (Republic of Kenya, 1981). The paper provides guidelines on all major issues related to food production and distribution, but makes no mention of RWH. Instead, it acknowledges and emphasizes irrigation as a means by which food production may be increased.

Fifth and Sixth National Development Plans

Section 6.137 of the fifth NDP (1984–1988) mentioned RWH for domestic purposes only, and emphasized irrigation for food production. Section 6.96 of the sixth NDP (1989–1993) stated that, in areas far from river basins, more efficient use of water for agricultural production in the arid and semiarid lands (ASALs) should be secured by water harvesting techniques. In addition, this NDP says that, in the higher rainfall areas of arid regions, various water conservation structures should be developed. In particular, this NDP indicated that integrated networks of drains and small dams would be constructed through food for work and *harambee* labour to provide high pay off supplementary irrigation. Section 10.53 of the NDP stated that, overall, the Government would encourage the development of water harvesting technologies appropriate for particular environments.

Development policy for the arid and semiarid lands, 1992

Section 7d of this paper (Republic of Kenya, 1992) on water resource development affirms that water resources are one of the main factors that limit the pace of development in ASALs. According to the paper, water harvesting and supply technologies that are sustainable and environmentally friendly would be given priority in development of the ASALs. In addition, this paper reiterated that, in areas far from river basins, more efficient use of water for agricultural production would be secured by water harvesting techniques.

National Draft Policy for the Sustainable Development of the Arid and Semi-arid Lands of Kenya (Government of Kenya, 2003)

The Kenya Government defined arid and semiarid lands (ASALs) on the basis of moisture availability (Milimo, 2004). Evapotranspiration in more than 30% of districts is more than twice the annual rainfall, which means that 30 districts are classified as ASALs and that 6 other districts have pockets of ASALs.

The first ASAL policy was formulated in 1979 (Government of Kenya, 2003). The policy had four main objectives: (a) resource conservation; (b) exploitation of productive potential; (c) development of human resources; and (d) integration of ASALs into the national economy. In 1983, these initial objectives were further elaborated in the fourth National Development Plan. In 1992, ASAL policies were augmented to include drought contingency planning and the involvement of communities and local institutions in the design, preparation and implementation of projects. The 2003 Draft Policy recognized that the 1979 policy did not result in significant improvement of the socioeconomic welfare of ASAL inhabitants. The policy lacked adequate support in terms of political goodwill, allocation of resources by the Government and a clear long-term vision. In addition, implementation was compartmentalized and instruments were not clearly defined. The only aspect that was implemented satisfactorily was the drought and disaster management component. This provided the foundation upon which the current policy was built. As a result, in August 2003, the Office of the President published a new ASAL draft policy with the vision of integrating social, economic and physical development activities as part of a long-term coherent goal.

In areas classified as arid, the new draft policy identified the following areas for intervention: natural resources and environmental management, water resources, social and community factors, livestock, infrastructure, small-scale enterprises, disaster/ conflict management, and support to small-scale rainfed dryland and irrigated farming. In the areas classified as semiarid, the following areas for intervention were identified: agriculture and livestock, environment, water resources, social and community factors, infrastructure, household food security, drought management and resource mobilization. Although the draft policy identified key sectors that are important to sustain livelihoods in the arid and semiarid areas, it failed to address the root causes of poverty and inequality in marginalized inhabitants (Milimo, 2004). Considering past investments and efforts, the draft policy should have placed more emphasis on social factors controlled by communities. For example, the draft policy did not articulate a coherent strategy for ensuring that the communities participate in decision-making and the implementation process.

Sessional paper no. 1 of 1994 on Recovery and sustainable development (Republic of Kenya, 1994)

This paper sets out Government policies and objectives for accelerating and sustaining development for Kenya to the year 2010. This policy document, like other similar papers on water and agriculture, emphasizes irrigation as a means for increasing agricultural productivity. Section 7.6.1 states that "Irrigation will remain an important means of increasing agriculture production". The policy document does, however, add that the use of water harvesting techniques of all kinds, particularly construction and de-silting of pans and rock catchments for agricultural production, should be encouraged. Section 7.7.7 adds that "…Water harvesting techniques of all kinds in areas far from river basins will be used for agricultural purposes".

Seventh National Development Plan 1994-1996

The seventh National Development Plan emphasized irrigation. This NDP did recognize water harvesting as promising, but it did not specify which type of water harvesting. As water harvesting is an umbrella term, it is assumed that rainwater harvesting is included. Just like other policy documents, the seventh NDP recognized water shortage as one of the main factors limiting development in ASALs. Section 9.10 a) stated that sustainable and environmentally friendly water harvesting and supply technologies would be given priority. This statement, however, referred only to surface and groundwater development.

Sessional paper no. 2 of 1996 on Industrial transformation to the year 2020 (Republic of Kenya, 1996)

This paper set out a strategy for Kenya's industrialization. It recognized water as a primary and locomotive input in industrial transformation in various sectors of the economy, including agriculture. The paper broadly stated that efforts would be made to impound water—presumably including RWH—when and where it occurred to enhance the health of people, livestock and plant life.

Eighth National Development Plan 1997-2001

This Plan conceded that overdependence on rainfed agriculture is one of the major problems in Kenyan agriculture and hinders agricultural growth in the country. However, RWH was not mentioned as a means of upgrading rainfed agriculture. Instead, this Plan, like many other policy documents, saw irrigation as the key to the development of agriculture, although water harvesting techniques "such as dams", were mentioned as a policy measure to improve agricultural productivity.

Sessional paper no. 1 of 1999 on Water resources, management and development (Republic of Kenya, 1999)

Kenya's first sessional paper on water tackled problems associated with water resource management, and suggested appropriate strategies and policies. Until this paper, there was no explicit water policy. The 1952 *Water Act*, which has now been superseded by the *Water Act* 2002 (Republic of Kenya, 2002), was the main policy guide on water development.

Section 3.2.3 of the sessional paper stated that the Kenyan Government would emphasize water programs that have a direct impact on vulnerable sections of society. One of the ways to achieve this would be to construct dams and pans in strategic locations and de-silt existing dams to harness rainwater for small-scale irrigation, livestock and other income generating activities. Section 3.4 conceded that

> "A lot of activities have been taking place in the water sector. Some of these activities have not been properly documented and this in most cases result in loss of valuable information and experiences. What is needed is a well planned monitoring to cover all the activities of the water sector actors".

This statement was a positive step towards recognizing and documenting RWH, which, for a long time had neither been documented, nor fully recognized in Government policy documents. The paper included a plan to publish a manual on water harvesting (surface runoff) techniques by December 1999 as part of the national initiative to promote water conservation for use in agricultural development. The policy statement recognized the important role of irrigated agriculture and the enormous amount of water it would require. To address this, efforts would be made to store rainwater and surface water runoff for irrigation and to encourage efficient irrigation practices.

The Water Act (Republic of Kenya, 2002)

The old water legislation did not harmonize or make adequate provision for legal and institutional frameworks. Three ministries, the Ministry of Water Resource Management and Development (now known as the Ministry of Water and Irrigation), the Ministry of Agriculture and Livestock Development and the Ministry of Local Government handled policy formulation, regulation and service provision. The lack of coordination and inter linkages between these three ministries led to conflicts about which ministry should take the lead in formulating policy, and problems in checks and balances in policy formulation and service provision (Fig. 52).

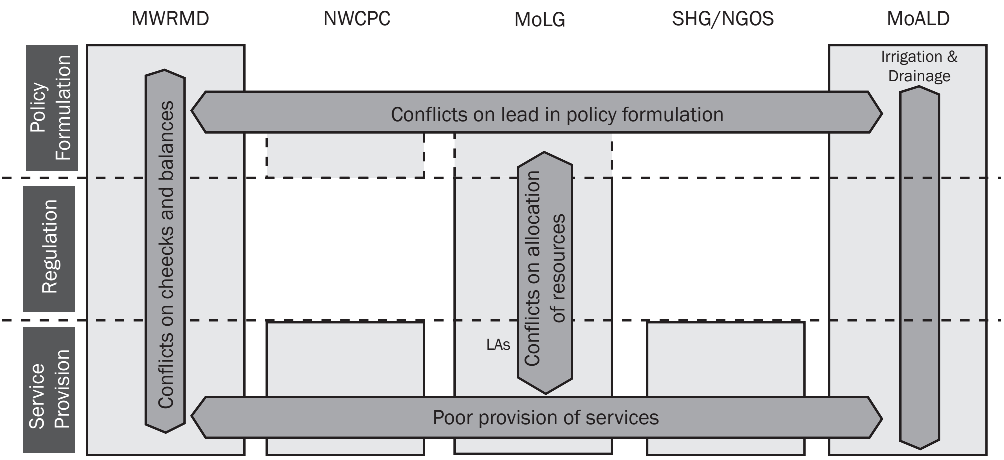

Figure 52: *The policy framework before the 2002 Water Act in Kenya*

The water sector conflict before the Water Act 2002

The 2002 *Water Act* (Republic of Kenya, 2002) separated the policy formulation, regulation, service provision and resource management functions (Fig. 53) and established new institutions at the national, regional and local level to deal with these four tasks. This separation ensures that there is clear policy accountability, a clear regulatory framework and improved service delivery. The Ministry of Water is moving away from service provision and delegating that responsibility to subordinate institutions created by the *Water Act*. The Ministry of Water will now regulate activities in the water sector and provide for the active participation of stakeholders, including the private sector, individuals and local communities, in the development and management of water resources in the country. The new institutions are:

- The Water Resource Management Authority (WRMA). This institution is responsible for regulation of water resource management issues, such as allocating water, protecting and conserving water sources, and water quality management.
- The Water Services Regulatory Board (WSRB), responsible for regulation of water and sewerage services.
- The Catchment Area Advisory Committees (CAACs), which advises on water resource conservation, use and apportionment.
- The Water Service Boards (WSBs), which are responsible for the efficient and cost-effective provision of water and sewerage services authorized by the license.
- The Water Resource Users Associations (WRUAs), which will ensure community participation in both management and development of resources.
- The Water Service Providers (WSPs). These may be communities, NGOs or autonomous entities established by the local authority or private sector which are responsible for water and sewerage service provision.
- The Water Services Trust Fund (WSTF), which will assist in financing the provision of water services to areas without adequate water services.
- The Water Appeal Board (WAB), which will be responsible for resolving appeals and disputes.

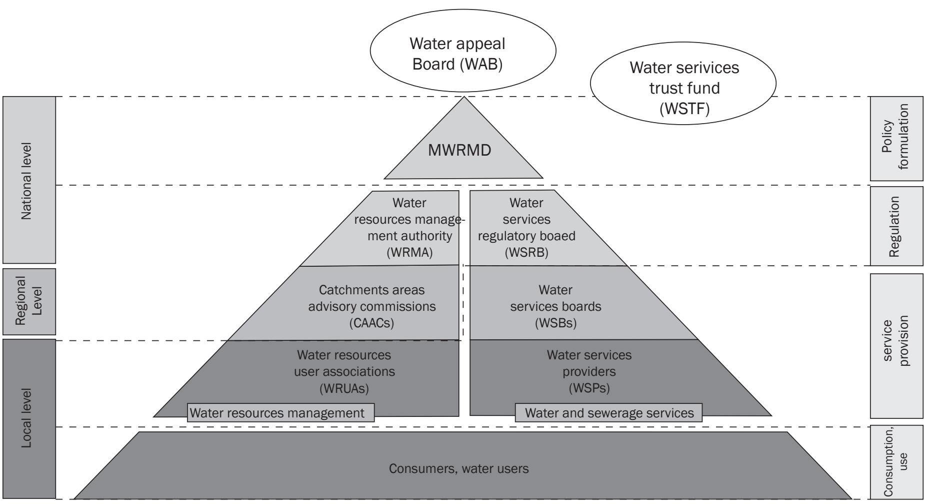

Figure 53: *The policy framework established by the 2002 Water Act in Kenya*

The 2002 *Water Act* (a revision of the 1952 *Water Act*) fails to include policies for RWH. This lack of recognition for RWH in the Act compounds the problems arising from the lack of guidelines and an appropriate legal framework for action.

Ninth National Development Plan 2002-2008

The seven-year ninth NDP was formulated at a time when the Kenyan economy was performing poorly. The worst affected sector was agriculture, whose contribution to GDP declined from 37% in the early 1970s to about 25% by the end of 2000.

With respect to the Government's plan for the ASALs, the ninth NDP included plans to develop water harvesting techniques to improve food security and to exploit surface and groundwater. Overall, the Plan emphasizes irrigation, which is seen as crucial to the development of agriculture in the country.

The Poverty Reduction Strategy Paper: Government Action Plan, September 2002

Milimo (2004) noted that the poverty reduction strategy paper (PRSP) links policy, planning and budgeting through Kenya's Medium Term Expenditure Framework (MTEF)—the resource envelope for financing identified sector activities. This recognizes that budgeting, policy and planning processes were not integrated and comprehensive. The objective of the MTEF was, hence, to impose discipline in planning and managing national resources by explicitly linking the policy framework and budgetary process. The PRSP advocates minimizing the role of the public sector in the economy through privatization, commercialization and contracting out. It envisages decentralization of some central government functions to improve service delivery. The PRSP acknowledges the importance of the natural resource base for agricultural development and notes the need for sustainable management. It promotes partnerships with Community Support Organizations and development partners to deliver agricultural extension services. It states that a land use policy should be formulated to help poverty alleviation: such a policy would guide sectoral decision-making.

The PRSP stresses the role of the budget as an instrument for stimulating growth. Yet the Kenya budgetary process, especially in the last decade, has failed to respond to development challenges, with the result that GDP and annual growth rates are declining and poverty is increasing.

Economic Recovery Strategy for Wealth and Employment Creation 2003 - 2007

In June 2003, Kenya's ruling party, The National Rainbow Coalition (NARC), unveiled its Economic Recovery Action Plan, the *Economic Recovery Strategy for Wealth and Employment Creation (ERS) 2003-2007*. In a review of Kenya's economic strategy for wealth and employment creation, Milimo (2004) noted that the Government plans to restore economic growth, generate employment opportunities to absorb the large army of unemployed, and reduce poverty levels. The ERS acknowledges the importance of integrating environmental sustainability into all development activities—energy, agriculture, tourism, forestry and cross-cutting sectors. The three main challenges for implementing the ERS are (1) ensuring that implementation is consistent with global and regional trends that demand sustainable approaches to development; (2) ensuring that implementation does not compromise environmental sustainability; and (3) ensuring that implementation devolves appropriate powers for decision-making from the centre to communities.

The ERS highlights the lack of a clear land policy and proposes to develop a policy that recognizes the need to halt the transfer of public land into private ownership. The ERS acknowledges the extent and diversity of Arid and Semiarid Lands and the neglect of pastoral and nomadic communities. It calls for the diversification of livelihood opportunities. As a result of such concerns, it was recommended that a Sustainable Environment Assessment of the ERS be undertaken. The National Environmental Management Authority (EMA), jointly with the Ministry of Planning and National Development, will facilitate the Assessment to:

- assess the environmental risks and opportunities presented by the implementation of the policies identified in the ERS; and,
- identify appropriate mechanisms to ensure that sound environmental management contributes to sustainable economic growth and lasting poverty reduction in Kenya.

The cost of re-engineering the Kenyan economy as proposed in the ERS is estimated at KShs461.7 billion (US$5,771 million). The Government cannot finance this level of funding and the private sector is expected to contribute KShs88.8 billion, or 19.2% of the total ERS budget. To achieve this level of financing, the Government will depend on the goodwill of international development partners.

Strategy for revitalizing agriculture 2004-2014 (Government of Kenya, 2004)

This national policy document sets out the plan of action, objectives and proposals for revitalizing the agricultural sector in Kenya. According to this paper, the Government is focusing on agriculture because:

- agricultural growth and development is crucial to Kenya's overall economic and social development; and
- the population is mostly rural and rural people derive their livelihood from agriculture.

Section 6.4.2 of the Strategy recognizes that surface water and groundwater are being over-extracted. This section also emphasizes that it is vital for the country to have a comprehensive plan for water management and to implement efficient water-use methods to ensure adequate water to meet increasing human and industrial requirements. One of the interventions to ensure efficient water use will be the promotion of water harvesting technology on farms to reduce reliance on river water resources and river pollution.

Section 6.4.3 of the Strategy concedes that many of the water schemes are on the brink of collapse. Measures to revive these schemes and bring them back into full production include:

- increasing the use of water harvesting techniques, such as roof catchments, pans, water holes, run off diversions; and
- promoting low-cost RWH and irrigation management technologies, such as smallholder drip irrigation systems to reduce risks due to the unpredictability of rainfall, and improved soil and water management practices.

With respect to the development of ASALs, measures to increase productivity include increasing water harvesting and management techniques, such as pans, water holes, and dams, and collecting runoff from roads.

Rainwater harvesting policy on water apportionment

Water in Kenya is partitioned between:

- domestic use,
- agriculture,
- wildlife and recreation,
- industry, and
- hydroelectric power generation and other purposes.

There is no RWH policy to govern the apportionment of water for the various sectors.

Section 32(2) of the 2002 Water Act states that "…Water for domestic use shall take precedence over the use of water for any other purpose…". This is as far as the policy on water apportionment goes. Beyond this, the policy does not direct apportionment, as different regions in the country have different water needs and requirements. However, the policy rules that a state scheme, regardless of the sector under which it falls, shall take precedence over all other schemes (including community schemes) for the use of water.

Rainwater harvesting policy trends over the years

The Government documents indicate that no clear-cut policy guidelines have been formulated to coordinate the practice and development of RWH in Kenya. In most policy documents, RWH is included in 'water harvesting' which, according to Wanyonyi (2004), is a general term that encompasses RWH. This hinders the optimal exploitation of the country's water resources and threatens environmental sustainability. The emphasis has been, and continues to be, on large-scale irrigation as a means of increasing agricultural productivity, despite the high costs of conventional irrigation, especially for small farmers.

The fourth NDP (1979–1983) was the first to clearly recognize rainwater conservation. It included plans to construct dams to conserve rainwater and surface runoff. With respect to RWH (for crop production) there is little or no continuity from one NDP to another. For example, whereas the fourth NDP includes plans for RWH, the fifth NDP does not.

This review of Government policies from the colonial period to date, indicates that only the sessional paper on water resource management (Republic of Kenya, 1999) and the strategy for revitalizing agriculture 2004-2014 (Government of Kenya, 2004) make outright mention of the need to harness and conserve rainwater.

12.2 Review of policy documents in Tanzania

This section reviews Tanzanian Government documents relating to water, food and agriculture in an attempt to determine its views on RWH.

Development plan for Tanganyika 1961/62–1963/64

The main objectives of this three-year plan were to develop agriculture and livestock industries. Supplementary objectives were to develop water resources and irrigation.

According to the plan, the responsibilities of the Water Development and Irrigation Division of the Ministry of Agriculture included the construction of water conservation, flood control, river training and irrigation works. The development plan did not include a clear-cut strategy for RWH.

Second five-year plan for economic and social development, 1 July 1969–30 June 1974 (United Republic of Tanzania, 1969)

With respect to water resource development, the second five-year plan asserted that the provision of adequate water supplies to rural areas was of high priority on both economic and social grounds. It added that water is a critical input into the agricultural and livestock industry.

The plan regarded irrigation as an important input in agriculture. It stated that the need to develop irrigation arises because of the uneven distribution and uncertain nature of rainfall. Referring to rural water supplies, emphasis was laid on the construction of boreholes "since dams are more costly and uneconomic because of the high rate of evaporation and siltation". The plan has no mention of RWH.

Water Utilization (Control and Regulation) Act 1974, No. 42 of 1974 (United Republic of Tanzania, 1974)

The definition of 'works' in this Act

> "includes canals, channels, reservoirs, embankments, weirs, dams, wells, boreholes and other works constructed for or in connection with diversion, damning storage or abstraction of water or for drainage or for the generation of water power or the use of water for industrial or other purposes or for the conservation of rainfall".

According to part III section 2(1)(b)

> "the owner or occupier of any land may construct any works thereon for the conservation of rainfall, otherwise than in a river or stream and abstract and use the water so conserved".

The Act ordered that a water right (permit) was required for the construction of any works, including constructions to conserve rainfall.

The Act stated that after the construction of works was completed, an officer should inspect the works and, if constructed to his satisfaction, he should certify the same in writing. It added

> "No certificate issued under this section shall be deemed to imply any guarantee by the government that the works are properly designed and constructed nor shall support justify any claim whatsoever against the government or any government officer in connection with such works".

This statement raises doubts as to whether the Government had sample designs for the construction of RWH technologies.

Agricultural policy of Tanzania 1983 (United Republic of Tanzania, 1983)

This policy makes no mention of RWH. Instead, the emphasis is on irrigation development. The paper states

> "It is clear that the country has a big potential for the development of both small scale and large scale irrigation schemes, therefore, new village irrigation schemes will be developed as quickly as this is possible, especially where they can be combined with the construction of mini hydro power units. Large scale irrigation schemes will be developed on the basis of their economic viability and the least cost approach. In all cases, steps will be taken to ensure that the irrigation works are properly maintained and managed; the possibilities of having more than two crops per year from irrigated areas will be explored".

Food and nutrition policy (United Republic of Tanzania, 1992)

Chapter 2, section 41, of the policy recognized that water contributes enormously to the improvement of food and nutrition.

Section 88 indicated that the ministry responsible for agriculture, livestock development and cooperatives has a very important role to play in ensuring that there is sufficient food for all people at all times. It added that one of the roles of the ministry in the achievement of food and nutrition policy in Tanzania is to ensure that irrigation farming aimed at the production of various crops is enhanced and sustained in the country.

RWH, unlike irrigation, was not included as one of the measures to be taken to improve and consolidate the production of various foodstuffs.

Agriculture and livestock policy (United Republic of Tanzania, 1997)

The main objective of the agricultural and livestock policy was to ensure food security at the national and household level. Management of rainwater for crop production was given very little mention in the strategy for rainfed crops. The policy conceded that crops and livestock are adversely affected by droughts and, in this respect, it identified irrigation as holding the key to stabilizing agriculture and animal production. The policy stated that water harvesting technologies were on hand and could be used to arrest and conserve runoff water from slopes and ephemeral streams. Development of irrigation systems, according to the policy, would be an important aspect of the agricultural development strategy and could help the nation achieve food security (by increasing production of rice and maize), and help farmers increase their productivity and income.

To improve the quality of life and social well being, the policy aimed to improve access to clean water in rural areas from 48.5 % of the population in 2000 to 55% by 2003. One of the ways in which this would be done was by promoting rainwater harvesting.

Poverty reduction strategy paper (United Republic of Tanzania, 2001a)

This document affirmed the correlation between agriculture, food security and poverty. As mentioned earlier, 80% of Tanzanians live in rural areas and depend on agriculture for their livelihoods. Thus, improving agriculture is the key to food security and alleviating poverty. According to the paper, a major concern of the poor is their vulnerability to unpredictable events, such as the famines that often result from floods and drought. Hence, to increase food security, the Government sought to reduce dependency on rainfed agriculture by supporting irrigation schemes in arid areas. The Government also set the target of improving access to adequate safe and clean water in the rural areas from 48.5% of the population in 2000, to 85% in 2010. In the long term, one of the strategies would be to promote RWH.

Rural development strategy (United Republic of Tanzania, 2001b)

The rural development strategy was developed in response to the unsatisfactory performance of the agricultural sector, the economic base of rural areas.

The rural development strategy states that one of the interconnected problems that affects efficient rural water supply is poor harmonization of water supply planning and utilization among its consumers. It adds that districts will normally plan for pump-based water supplies and neglect other resources, such as hand-dug wells and water harvesting. One objective of the rural water supply and sanitation program will be to expand coverage of water supply systems by utilizing appropriate sources. One way in which this will be done, according to the document, is by sensitizing communities to harvest rainwater where climatic conditions permit. The document states that

> "Expanding irrigated agriculture would offer considerable potential in Tanzania, however many large irrigation schemes built in the past have neither generated adequate economic rates of return nor benefited poor small holders because of poor management. Poor management of such schemes has often resulted in environmental damage through water logging, contaminated run off, erosion and land degradation. Thus emphasis will be given to designing low cost and technologically appropriate *irrigation and water control* systems that can be managed by local communities and thus take into account the many competing demands for water".

Agricultural sector development strategy (United Republic of Tanzania, 2001c)

Agriculture is a major sector of the Tanzanian economy and accounts for over half of GDP and export earnings. Among the factors that contribute to risk in Tanzania's agriculture are the unpredictability of rainfall, and droughts and floods. According to the strategy, soil and water management practices must be improved to reduce these risks and improve the productivity and profitability of agriculture.

In this regard, one of the measures that the Government will take is to enhance the efficiency of water utilization, especially of rainwater, by promoting better management practices. A comprehensive program for integrating soil and water conservation, RWH and storage, irrigation and drainage will be developed by the Ministry of Water and Livestock Development (MWLD).

National water policy (United Republic of Tanzania, 2002)

This water policy is a revision of the 1991 policy and its main objective is to develop a comprehensive framework for sustainable development and management of the nation's water resources. The policy document addresses three sub-sectors: water resource management, rural water supply and urban water supply and sewerage. The paper confirms that agriculture in Tanzania is predominantly rainfed and, because of inadequate and unreliable rainfall, the paper advocates irrigation as the answer to drought and food security.

Section 4.2.1 states that, where feasible and necessary, RWH among other activities, such as wastewater recycling and desalination of seawater, will be used to increase the availability of water resources.

According to the paper, the reasons for failure of some of the rural water supply schemes included inappropriate technology, unsuitable location of facilities, and lack of social acceptability and affordability. Communities will be encouraged to make technology choices appropriate to their circumstances, particularly those which have low operation and maintenance costs. In section 2: Rural water supply, RWH has been recognized. According to the paper, the Government's goal is to make more water available to rural communities through RWH technologies. It recognizes that RWH is a good source of water especially in ASALs, where it may prove to be the only reliable source of water in the dry season.

The paper adds that, in order to make more water available to the rural areas through RWH, the following will be undertaken:

- communities will be made aware of and encouraged to use RWH technologies;
- research on RWH technologies will be enhanced; and
- RWH will be promoted to stakeholders by raising awareness and training.

It is worth noting that the water policy gives more power to communities, especially in rural Tanzania, to start and manage their own water supply projects. The earlier policy (1991) had placed that responsibility on the Government.

The national water policy 2002 is the first policy document to include rainwater harvesting, even though 'green water' harvesting is not specifically mentioned.

Rainwater harvesting policy on water apportionment

There is no RWH policy on water apportionment in Tanzania. However, water in Tanzania is partitioned between:

- hydropower generation,
- domestic use,
- agriculture use, and
- industrial use.

Most water is used for domestic water supplies. According to the national water policy, 2002

> "Water for basic human needs in adequate quantity and acceptable quality will receive highest priority. Water for the environment, to protect the eco-systems that underpin our water resources, now and in the future will attain second priority and will be reserved. Other uses will be subject to social and economic criteria which will be reviewed from time to time".

Rainwater harvesting policy trends over the years

Even though RWH has been practiced for a very long time and despite its numerous advantages and potential benefits, there is no clear-cut policy to guide and coordinate the practice and development of green water harvesting in Tanzania, even though there are clauses in policies that support RWH. In general, especially from the 1960s to the 1980s, the stress was on irrigation, which was seen as the answer to the development of the agricultural sector. This is evident from the development plans and the first agricultural policy drawn up in 1983. Only the 2002 *National water policy* specifically recognizes RWH as a means of increasing agricultural productivity.

The *Water Utilization (Control and Regulation) Act* (United Republic of Tanzania, 1974), is the umbrella legislation for the management of water resources in Tanzania, but does not effectively address RWH. The Act defines 'works' as any structure for the purpose of conserving rainfall and requires permits for the construction of any such 'works'. This is as far as the legislation goes with respect to RWH.

Impact and advantages of rainwater harvesting

Considering that an estimated 80% of Tanzania's population lives in rural areas and that agriculture plays a vital role in their livelihoods, RWH has the potential to reduce poverty levels. As a supplement to rainfall in rainfed agriculture, RWH can increase crop productivity, increase household food security, promote self sufficiency and even offer farmers a source of income through the sale of surplus produce.

In rural Tanzania, smallholder farmers practice RWH for rice production and other crops. The *majaruba* (embankments) are constructed before the rains to trap water during the rainy season. Over the years these *majaruba* have spread throughout the Mwanza, Shinyanga, Tabora and Mara regions around Lake Victoria. During the El Niño rains (1997/1998), this technique worked so well that the price of rice fell to a level where everybody could afford to buy rice—from TShs200/kg to TShs50/kg. RWH is a strategy for sustainable development of dry areas. By supplementing rain in times of low rainfall, it plays a major role in reducing the effects of drought. In addition, harvesting rainwater lessens the impact of erosion and flooding caused by runoff and, at the same time, puts a valuable resource to work. Rainwater harvesting technologies for crop production are more reliable, more environmentally friendly and more cost effective than conventional irrigation schemes, especially in rural areas. With basic knowledge, they are easy to operate and manage. Last, but not least, rainwater can be collected at the point of use without having to transport it over long distances.

12.3 Review of policy documents in Uganda

Government of the Republic of Uganda. Plan for modernization of agriculture: eradicating poverty in Uganda (Government of the Republic of Uganda, 2000)

The *Plan for Modernization of Agriculture* (PMA) is a holistic framework for eradicating poverty through multisectoral interventions that enable the people to improve their livelihoods in a sustainable manner.

Modernizing agriculture will contribute to raising the incomes of the poor by boosting farm productivity, increasing the share of agricultural production that is marketed, and creating on-farm and off-farm employment. The agricultural sector presents a great opportunity for poverty eradication because it employs over 80% of the labour force, and because agricultural growth can be accelerated substantially. Over 85% of Uganda's population lives in rural areas, where agriculture is the major contributor to their livelihoods. From the poor household's perspective, improving agriculture-based livelihoods means transforming agriculture by enhancing their capital assets—natural, physical, financial, human and social. The interventions in this document are, therefore, intended to augment poor farmers' capital assets, thus improving their livelihoods in a holistic manner.

Under the PMA, the Government will:

- finance advisory services for subsistence farmers to deliver knowledge for agricultural transformation, product processing and marketing;
- finance agricultural research for smallholders to develop and promote productivity-enhancing technologies;
- finance control of endemic diseases and pests;
- finance capacity building for the production of foundation seed;
- provide regulatory services, and improve fertilizer and chemical use in order to minimize environmental damage;
- finance the collection of agricultural statistical data, production and marketing information for planning and analytical purposes;
- finance the implementation of land reform, so that potential investors are ensured of secure tenure;
- finance capacity building of agriculture-related institutions including private/NGO rural financial institutions;
- set policies and regulations to foster the expansion of the private sector to encourage commercialisation without compromising food security;
- construct fish landing sites to facilitate fish handling, quality control and monitoring;
- finance development of irrigation information; and
- finance capacity building for subsistence farmers in water harvesting and soil and water conservation.

Natural resources must be used and managed in a manner that ensures their availability to both present and future generations. The key resources are land, water, forests and other aspects of the environment. There is already a *Land Act* and what remains to be done is to implement the Act. This means developing a comprehensive land use policy to facilitate the growth of land markets, efficient land use and management, as well efficient land registry and administration systems. The main focus on water for production will be demonstrating on-farm small scale irrigation and water harvesting technologies. Soil and water conservation methods will be researched and appropriate technologies demonstrated to farmers. Agroforestry will be among the mainstream activities of agricultural advisory services and agricultural education curricula. Environmental issues and concerns will be incorporated in all programs to be implemented under the PMA.

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Chapter 13

Monitoring and evaluation

A strong monitoring and evaluation (M&E) system helps ensure that a rainwater management (RWM) strategy meets its main objective of fostering positive change, and also that the strategy adapts to evolving needs and conditions. Although M&E is a vital component in the success of any strategy, development and implementation is seldom allocated sufficient time, thought, and human and financial resources.

Monitoring and evaluation involves:

- Monitoring implementation—to ensure that the *actions* outlined in the strategy are being taken and that resources are being allocated and used effectively.
- Monitoring the *outcomes* of those actions—in terms of investments in infrastructure and changes in policies, institutional frameworks, and management instruments.
- Evaluating progress towards the achievement of *goals and objectives* in relation to actions.
- Using the information gained to refine the strategy and to inform decision making at different levels—from national planning to water user behaviour.

Box 6. What is monitoring and evaluation (M&E)?

Monitoring: The continuous assessment of the progress and performance of a development intervention.
Evaluation: The end or ex-post assessment of an intervention, its impacts and lessons learned.

Objectives of M&E:
- Keep activities on track in relation to objectives.
- Ensure that implementation procedures are appropriate.
- Enable evaluation; see what works and what does not.
- Learning.
- Prioritize scarce resources (Accountability, transparency?).

By 1990 there was increased recognition that many development projects had failed to achieve targeted social and economic goals. M&E emerged in a climate characterized by New Public Management, 'rolling back the state', mushrooming of NGOs, and liberalization of economies and participation.

13.1 An overview of the role indicators play in the M&E process

Indicators are the basic building blocks of monitoring and evaluation systems. They are also a part of assessment, which plays a crucial role at the beginning of the strategy formulation process and provides the baseline needed for M&E during implementation. As a part of assessment and M&E systems, indicators help to answer key questions at various stages, such as where the strategy is now, where it intends to go, whether the right path has been taken to get there and, finally, whether the strategy has been achieved.

Where is the strategy now?

As part of a baseline assessment, indicators help to determine what the problems are, where they are, and how severe they are. Depending on the resources available and the strategy chosen, the baseline assessment may be a comprehensive assessment of water resource requirements and availability, or a targeted assessment focusing on identified problem areas. Some of these indicators will feed into the monitoring and evaluation system—providing a baseline against which to measure progress during implementation. These might include indicators of water availability, water quality, irrigation performance, aquatic ecosystem health, incidence of water-borne disease, incidence and impacts of flood or drought, and access to water supply and sanitation. They may also include sustainable development indicators that are not as clearly water-related, such as child mortality, the percentage of boys and girls in rural areas attending school, and changes in the contribution of certain sectors to the GNP.

What is the intended destination?

Information provided by the baseline assessment indicators can help decide on priorities and can serve as a useful input into stakeholder dialogues during the strategy formulation process. Indicators may also help to assess the effectiveness of existing institutions, policies, regulations and help identify objectives. Once priorities, overall goals, objectives and actions have been agreed, the process of defining indicators for M&E can help to set and refine specific targets.

Box 7. What can indicators do?

Indicators can help to answer the questions 'Where are we now?', 'Where do we want to go?', 'Are we taking the right path to get there?' and 'Are we there yet?'

Has the right path been taken to get there?

As part of an M&E system, indicators can signal when a strategy is off track—when actions are not being taken or are not having the desired outcomes and impacts. At the day-to-day project management level, indicators can be used to track inputs: are the human and financial resources allocated to different activities adequate and are those resources being disbursed and used efficiently?

Has the strategy been achieved?

Evaluating progress towards goals and objectives is important, not just from the standpoint of identifying when and where adjustments are needed, but also for accountability, and building and maintaining support for the strategy.

Basic steps in developing indicators as part of an a M&E system

There are various approaches to defining indicators. The model below is one example.

Step 1
Make sure that targets associated with strategy goals, objectives and actions are clearly defined and agreed upon; and that the inputs necessary to carry out actions are identified.

A good monitoring and evaluation system will take into account possible tradeoffs and unintended consequences involved in any course of action.

The following example defines a hypothetical set of objectives and actions, with targets and indicators, to contribute to Millennium Development Goal (MDG) 1. The example is intended to illustrate the relationships between these different elements of an RWM strategy and, in particular, to offer insight into the process of defining targets and indicators. It is not intended to be comprehensive, or to serve as a recommendation of any particular objectives or actions.

GOALS

Example of a goal:

- Millennium Development Goal #1: Eradicate extreme poverty and hunger.

Targets:

- Target #1: Halve, between 1990 and 2015, the proportion of people whose income is less than one dollar a day.
- Target #2: Halve, between 1990 and 2015, the proportion of people who suffer from hunger.

(Impact) Indicators for Target #1:

- MDG Indicator #1: Proportion of population living on less than $1 per person per day.
- MDG Indicator #2: Poverty gap ratio (incidence × depth of poverty).
- MDG Indicator #3: Share of poorest quintile in national consumption.

OBJECTIVES

Example of an objective:

- Fully and sustainably harness rainwater and groundwater resources in the country's arid and semiarid areas to improve the income-generating potential of small-scale agriculture in those areas and provide improved access to safe water for household use.

Example of a target:

- Between 2005 and 2015, increase average annual income of farmers with plots of less than 1 hectare by at least US$2 per day.

Example of an impact indicator:

- Average annual income, by district, of farmers with less than 1 hectare of land.

ACTIONS

Example of an action:

- Create an integrated program targeted at farmers with plots of less than 1 hectare to promote sustainable groundwater development and rainwater harvesting in combination with supplemental irrigation.

Examples of targets:

- By 2009, 50% of farmers identified by baseline study are reached by program.
- By 2010, *at least* 80% of farmers identified by baseline study are reached by program.
- By 2015, 100% of farmers identified by baseline study are reached by program.
- By 2015, total groundwater withdrawal reaches 90% of safe yield[4].

Some examples of process indicators (unless otherwise noted, these indicators are to be applied by district, annually):

- Financial resources allocated to the development and implementation of program.
- Feasibility/baseline study completed; target districts identified by 2007.
- Groundwater assessment and monitoring system in place in target districts by 2007.
- System for regulating and licensing groundwater withdrawal put into place by 2007.
- Number of check dams sited and constructed with community participation.
- Percentage of farmers who default on low-interest loans.
- Number of agricultural extension officers trained in supplemental irrigation and water harvesting.

Some examples of outcome indicators:

- Number of low-interest loans granted for investing in supplemental irrigation technologies, water harvesting, and groundwater development (monthly).
- Number of farmers served by extension officers trained in supplemental irrigation and water harvesting.
- Number of groundwater licenses granted.
- Total groundwater withdrawal expressed as a percentage of safe yield.

The RWM strategy or plan may take as its overarching goal one or more of the development goals that the country is committed to achieving and that are affected, directly or indirectly, by water resources development, management and use. In the case of national and international development goals, often targets and indicators will already have been defined. Targets and indicators defined for the objective should relate clearly to the targets and indicators defined for the goal. In this example, accomplishment of the target, as measured by the impact indicator, would theoretically contribute directly to meeting MDG target #1, according to MDG indicator #1—the proportion of the population living on less than $1 per person per day. Additional targets would be needed to address the household water supply and sustainability components of the objective. The RWM strategy or plan needs to define a set of actions to achieve each objective—that is, infrastructural development investments and changes in policies, institutions and management instruments. This might be *one* of the actions under the above objective. Targets, process indicators, and outcome indicators need to be defined for each action. Notice that this example includes short-, medium-, and long-term targets. Process indicators, used to measure the process of implementing the action, can be quantitative or qualitative; in some case a checklist item may be more appropriate.

This example contains a mix of quantitative indicators and checklist items. The outcome indicators relate directly to targets set for this action. The assumption behind these targets is that if the program reaches the farmers, their incomes will improve. Testing this involves correlating the results of the outcome indicators with results from the impact indicator defined for the objective.

Objectives can be thought of as the major water and development challenges that need to be addressed to achieve the defined goals. For a country with many poor people dependent on marginal rainfed agriculture, rainwater harvesting might be a possible objective under MDG 1. Objectives and actions will often contribute to more than one target, and even more than one goal. The example used here contributes to MDG #1, targets #1 and #2, also to MDG #7, target #9 (integrating sustainable development principles into policies and programs), and target #10 (sustainable access to safe drinking water and sanitation).

Step 2

Define indicators for each target based on stakeholder consultations and on criteria, such as relevance, reliability, and cost-effectiveness.

Involve stakeholders who cause or are affected by the problem or issue addressed in the target; who have relevant information or expertise; and who will be responsible for implementing indicators.

Step 3

Select indicators to track human and financial resources and ensure that they are being disbursed and used efficiently.

Step 4

Check to make sure that indicators relate clearly to targets, and that these in turn support the achievement of actions, objectives and goals. Identify and fill gaps.

Refine indicators and/or targets as necessary. This step may involve taking an inventory of indicators that are already in use in the country to eliminate redundancies, and also considering the relationship of national M&E efforts to international monitoring programs—such as the World Water Assessment Programme.

Step 5

Calculate human and financial resources needed to apply the indicator package.

Evaluate whether the package is a good investment; that is, whether the human and financial resources required are commensurate with the value of the various indicators employed.

Step 6

Agree on the agencies/institutions that will be responsible for applying the different indicators, how, and how often.

Step 7

Determine how the information resulting from the different indicators will be managed. For example, how it fits into decision-making processes, both specifically related to the strategy but also ongoing policy and planning processes; how information will be amalgamated to get a more comprehensive picture of progress; and how it will be communicated to stakeholders.

Step 8

Include requirements for the M&E package in capacity building plans, budgets, and staff allocation.

13.2 Some nuts and bolts of establishing an M&E system

Determining the frequency of monitoring and reporting

The frequency of monitoring and reporting should be based on how rapidly conditions are changing and the significance of the changes. In general, processes need to be monitored frequently and need to be part of regular management activities. Action monitoring is generally tied to specific milestones. Objectives have a longer time horizon—depending on the specific objective, this may mean monthly, quarterly, biannual, or annual monitoring. Progress on goals may take many years to emerge; this may mean annual monitoring, but reporting every three years or even every five years—again depending on the targets defined.

Coordinating monitoring efforts across agencies

Creating an M&E system for an integrated water resource management (IWRM) strategy often involves linking the data-collection activities of multiple agencies. This can be a challenge, especially if agencies are not used to working together, much less sharing information. One possible solution is to create a monitoring and evaluation unit or task force, with representation from organizations and agencies carrying out relevant monitoring activities. Also, it is necessary to make sure that agencies understand how the data they provide is being used and that the flow of information is not solely one way. Stakeholders that should be involved include those who cause or are affected by the problem or issue to be addressed; those with relevant information or expertise; and those who will be responsible for implementing indicators.

Box 8. Definitions in monitoring and evaluation (M&E)

The terminology used in M&E is still far from standardized, resulting in a confused tangle of competing definitions. The definitions below are in accord with the framework employed in monitoring the Millennium Development Goals (MDGs) and with the most common logical framework definitions.

- Goals are broad, qualitative statements about what is to be achieved or what problem is to be solved. For example, Millennium Development Goal 1 is to eradicate extreme poverty and hunger. In the case of an RWM strategy or plan, using already accepted national and international goals is one way of linking into larger sustainable development and poverty initiatives, such as efforts to meet the MDGs, national sustainable development plans, etc.

- Objectives are the means identified to achieve goals, or the major water and development challenges that need to be overcome to achieve the goals. For example, reducing farmers' vulnerability to drought in rainfed areas might be an objective associated with the goal of eradicating extreme poverty and hunger. (The Millennium Declaration does not define objectives, since they will differ from country to country.) Often the terms 'goals' and 'objectives' are used interchangeably. Here we choose to make the distinction between 'goals', as overarching aims, often defined by larger national (and international) priorities, and 'objectives', as specific aims to be achieved that are determined by the goals.

- Actions are the specific activities identified to accomplish objectives. These encompass infrastructural development and changes in policies, institutions, and management instruments. All the above goals, objectives and actions have corresponding targets and indicators.

- Targets make goals, objectives and actions specific, with defined and measurable criteria for achievement and timetables. For MDG 1, one of the targets is to halve, between 1990 and 2015, the proportion of people who suffer from hunger.

- Indicators are measures selected to assess progress towards the targets associated with goals and objectives and the accomplishment of actions. For example, the prevalence of underweight children under five years of age and the proportion of the population below the minimum level of dietary energy consumption are used as indicators for the Millennium Development target on hunger. Indicators can be further subdivided into:
  1. Process indicators, which monitor the basic progress of implementing the actions outlined in the strategy. This includes monitoring implementation processes and also the tracking of inputs—the people, money, equipment needed to achieve actions.
  2. Outcome indicators, which monitor the direct results of actions. (Sometimes used interchangeably with impact indicators.)
  3. Impact indicators, which monitor progress towards achieving goals and objectives.

The challenge of linking actions, outcomes and impacts

As suggested in the preceding section, decisions on what and even how to monitor cannot be made independently from the definition of goals, objectives, actions and targets, all of which should relate to each other in a logical way. Establishing these logical relationships is a large part of developing an effective M&E system, as well as an effective strategy.

In particular, establishing cause–effect relationships between the outcomes of actions—

the direct results of the strategy's activities—and impacts, in terms of the strategy's larger goals and objectives, can be difficult. This is partially because impacts take time to emerge, but also because progress on the ground can rarely be attributed to a single cause. Usually it is the product of multiple forces—not all of which lie within the strategy's scope of action—which are often too numerous and/or complex to feasibly monitor. That said, there are ways around this dilemma: (1) making initial assumptions regarding causal links explicit and regarding these as hypotheses that the M&E system will test; (2) identifying factors outside the strategy that could influence impacts and choosing which ones to monitor based on the likelihood and potential degree of influence; (3) setting and monitoring short-, medium-, and long-term targets; and, most importantly, (4) developing an M&E system that is geared towards learning and adaptation.

Defining the links in the chain

In monitoring and evaluation it is important to develop indicators to monitor all the key links in a chain of results or logical hierarchy. To take a relatively simple example at a sub-national level, let us say that the goal is to improve the livelihoods of fishers in a coastal ecosystem. One of the objectives identified under this goal is to reduce the high levels of pesticides in the river feeding the ecosystem, based on the assumption that high pesticide levels are having a negative impact on the catches of the area's fishers.

The primary action identified to address this problem is to introduce an integrated pest management program in the upstream agricultural area. There would need to be indicators to track (1) if the action was resulting in a reduction in pesticide use by farmers, (2) if the changes in farmer behaviour were resulting in a significant reduction in the pesticide levels in the river, and (3) if this improved water quality was resulting in improved catches and increased income for the fishers. Without developing and analyzing indicators together in the context of a logical chain of results, it is difficult to identify the problem when goals and objectives are not reached.

A good M&E system will also take into account possible tradeoffs and unintended consequences involved in any course of action. To continue with the above example, this would also mean monitoring agricultural productivity in the upstream area where integrated pest management was introduced to make sure that there was not a resulting decline in crop yields. It might also mean monitoring the market price of fish, to make sure that increasing the fishers' catches does not result in a glut in the market and a corresponding drop in prices. Indicators cannot be identified in isolation—they must emerge from agreed goals and objectives, and the actions needed to achieve them.

Managing data

Investment in designing a good data management system is money well spent. When considering the design of such a system, consider current needs as well as future ones. Solicit input from a range of end users of the system.

Communicating with stakeholders

An often neglected aspect of monitoring and evaluation is communicating results to stakeholders—this includes those directly involved in implementing the strategy as well as the general public. Regular stakeholder communication can help to mobilize support for the strategy and to increase accountability. Effective communication means packaging information in a way that is readily understandable to the target group and that addresses their needs or concerns.

Linking to decision-making and planning processes

Part of the ongoing work of the strategy process is to support better decision-making. M&E is a valuable tool in this effort—but only if M&E results are provided to decision-makers at all levels in a readily accessible form that meets the end users' needs.

Building a system that encourages improvement and adaptation

A good M&E system should support improvement and adaptation at several different levels. At the project management level, an M&E system should provide information needed to improve the efficiency of the implementation process and the performance of those involved. At a strategic level, it should also support regular reviews of the strategy itself—to revaluate chosen courses of action and take into account changing contexts. The M&E system itself should also be subject to regular reviews.

13.3 Key lessons

Key lessons in M&E are:

- Indicators should clearly relate to the targets defined for the strategy's actions, objectives and goals.
- Indicators need to be defined and analyzed as part of a logical framework of relationships between goals, objectives, actions and the intended outcomes and impacts. In some cases these relationships may only be hypothesized, in which case part of the work of the M&E system is to test hypothesized links.
- Stakeholders should be involved in defining indicators and should clearly see how the information provided by the indicator relates to their concerns and activities.
- It should be clear who is responsible for applying each indicator and how the resulting information will be utilized in the process—who needs it when.
- M&E needs to take into account that impacts may differ according to location and the gender and socioeconomic status of beneficiaries.
- The human and financial resources required for M&E need to be considered and factored into budgets and capacity-building needs.
- The results of M&E activities should be communicated regularly to stakeholders—to help mobilize support for the strategy and to increase accountability.

The development of rainwater harvesting systems for agricultural production has accelerated in recent years due to the scarcity of water resources and the ineffectiveness of traditional systems. In order to analyze trends and the long- and short-term efficiency of these projects, the development of M&E systems is necessary. The results of evaluation can be used to analyze different technical, economic, and social aspects of projects at the implementation and operational stages. The preparation of reports for managers at different levels of decision making for these systems will provide a basis for project control and operational management.

In general, monitoring and evaluation systems can be classified into two categories:

1. Those based on economic analysis and
2. Those based on multiple-criteria decision-making techniques.

The systems in the first category are highly effective if information about the interest rate, impact of inflation, and costs and benefits is available and is analyzed by experts. In many cases, evaluation criteria cannot be measured in monetary units and, even if they can, the information on cost is usually highly uncertain especially in developing countries because of the state of their economies. As a result, multiple-criteria decision making has been the basis for developing evaluation and monitoring systems.

Indicators for different aspects of project progress, including efficiency of use, are the main elements of these systems. These indicators can be quantitative and/or qualitative. Selection of a suitable method for data gathering is also important. Furthermore, the data gathered by different evaluators should be consistent and comparable.

Different methods have been suggested to deal with multiple-attribute decision-making (MADM) problems for discrete variables. Of all the methods suggested, the analytical hierarchy process (AHP) has been found to be the most suitable method for the study of rainwater projects because of their nature and the structure of the relevant criteria. The method was used in a master plan to estimate the proportion of contamination from different water pollution sources in the central part of Iran.

Indicators and their hierarchical structure

To monitor and evaluate a complex system, a set of indicators that covers different aspects of that system is necessary. These indicators should be measurable, correlated, have a hierarchy structure, and should also be independent at each level. Properties of the indicators and their correlation structure are identified depending upon the decision-making process as well as on the decision maker's perception of progress.

Different qualitative and quantitative indicators, such as indicators for analysis of physical and financial progress, the long- and short-term impact of the projects, and the risk factors, can be considered. Although of value to RWH systems, data on climatic, cultural, and social conditions that affect agricultural projects is often insufficient but should be taken into consideration. The indicators selected can then be classified into two general categories: quantitative and qualitative progress, and effectiveness of the project. In the progress category, the following indicators are considered:

- *Financial Progress*: This shows the status of the budget (from different sources used and allocated such as private investment and loans) and how it compares with the timetable for spending for the projects.
- *Physical Progress*: This shows the status of civil activities compared to the timetable for the projects and the quality of implementation.
- *Risk*: This shows the state of steadiness and serviceability of the system. The results of reliability, vulnerability, and resiliency analysis of the projects should be demonstrated. The reliability indicator represents the frequency of success in satisfying predefined targets. Vulnerability is the probable intensity of failures. Resiliency indicates a measure of the time necessary to return to normal operation after each failure in system operation.
- *Technical Soundness*: The quality and impact of the projects on the improvement of technical levels such as changes in sampling and monitoring, training programs for farmers, and qualitative and quantitative tests are considered in this category.

Using these indicators, decision makers should be able to monitor and evaluate the progress of project implementation. To evaluate the effectiveness of the projects, indicators of short- and long-term effects are considered:

- *Short-term Effects*: The increase in water use efficiency, production increase, improvement of crop quality, optimal distribution of fertilizers and pesticides, and the increase in farmer income are some of the short-term effects that are considered in this category.
- *Long-term Effects*: The improvement of social and cultural conditions, improvement of sanitary conditions, change in soil quality, decrease in the employment rate, and the expected long-term benefit over cost ratio are some of the impacts that are considered.

Monitoring, evaluation and reporting are often weak spots in rainwater harvesting projects. Too many projects fail to collect data at even the most basic level. For example, crop yields and tree heights are often just estimated. It is also very rare to find any information on the frequency or depth of water harvested. Without a basic monitoring system, projects are starving themselves of data for evaluation. Without clearly written reports, that are widely circulated, projects are denying others important information. A suggested monitoring format is presented in Table 22.

Table 22: *Suggested monitoring form for water harvesting projects*

1. HYDROLOGICAL DATA	
- rainfall (standard gauges at important sites)	
- runoff (at least visual recordings of occurrence)	
2. INPUTS	
- labour/machinery hours for	(a) construction
	(b) maintenance
	(c) standard agricultural operations
3. COSTS	
- labour/machinery use in	(a) construction
	(b) maintenance
	(c) standard agricultural operations
4. OUTPUTS	
- crops: yields of treated plots compared with controls	
- trees: survival and growth rates	
- grass/fodder: dry matter of treated plots compared with controls	
5. ACHIEVEMENTS	
- area (hectares) covered each season	
- number of farmers/villagers involved/benefiting	
6. INCENTIVES/SUPPORT	
- quantity and costs	
7. TRAINING	
- number of training sessions	
- attendance/number of trained personnel	
8. EXTENSION	
- number of farmers visited	
- number of field days and attendance	

Note: SUMMARY SHEETS of data are very useful. These could include the following: labour/ha, cost/ha, average yield, increases over controls, total area of land treated and number of beneficiaries.

(**Endnotes**)

1 The study calculated annual returns as a ratio of the benefits to annual costs of water and soil conservation measures. This can be regarded as a variant of gross margin analysis.

2 At the time of this study the average exchange rate was TShs 850 = US$1

3 This case study was extracted from the book chapter: Lazaro, E.A, Senkondo, E.M. and Kajiru, G.J. 2000. Fitting RWH into the Social-economic Environment: Ensuring Acceptability and Sustainability. In: Hatibu, N. and H.F. Mahoo (Eds). Rainwater Harvesting for Natural Resources Management. RELMA Technical Handbook 22:39-57.

4 Rate of groundwater extraction from a basin for consumptive use over an indefinite period of time that can be maintained without producing negative effects.