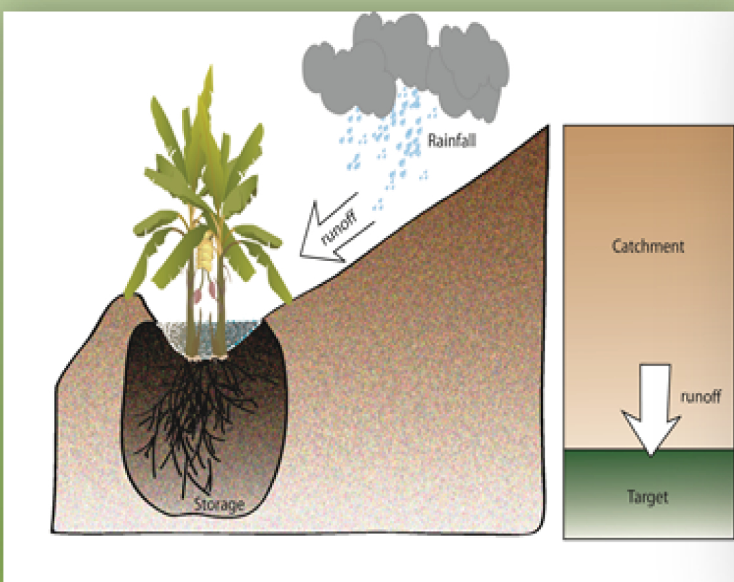
NILE BASIN INITIATIVE
Initiative du Bassin du Nil

RUNOFF HARVESTING FOR CROP PRODUCTION:

PRACTICAL SOLUTIONS FOR DRY LAND AGRICULTURE



Nile Basin Initiative – NELSAP
Regional Agricultural Trade and Productivity Project (RATP)

Training Manual 1

2012

RUNOFF HARVESTING FOR CROP PRODUCTION: PRACTICAL SOLUTIONS FOR DRY LAND AGRICULTURE

TRAINING MANUAL No. 1

Nile Basin Initiative (NBI)
Regional Agricultural Trade and Productivity Project (RATP)

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2012

Citation
Mati, B.M. 2012. *Runoff Harvesting for Crop Production: Practical Solutions for Dryland Agriculture.* Training Manual 1. Nile Basin Initiative (NBI), Nile Equatorial Lakes Subsidiary Action Programme (NELSAP) - Regional Agricultural and Trade Programme (RATP), Bujumbura, Burundi.

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About this Training Manual

The Nile Basin Initiative (NBI) is a partnership of the riparian states (Burundi, Democratic Republic of Congo, Egypt, Ethiopia, Kenya, Rwanda, Sudan, Tanzania and Uganda**,** Eritrea is participating actively in the NBI as an observer) that seek to develop the river in a cooperative manner, share substantial socioeconomic benefits, and promote regional peace and security through its shared vision of "sustainable socioeconomic development through the equitable utilization of, and benefit from, the common Nile Basin water resources". NBI's *Strategic Action Program* is made up of the *Shared Vision Program (SVP) and Subsidiary Action Programs (SAPs).* The SAPs are mandated to initiate concrete investments and action on the ground in the *Eastern Nile (ENSAP) and Nile Equatorial Lakes sub-basins (NELSAP).*

NELSAP through its sub basin programs implements pre-investment programs in the areas of power, trade and development and natural resources management. As part of its pre-investment framework, the Regional Agricultural Trade and productivity Project (RATP), in concert with the NELSAP, intends to promote and disseminate best practices on water harvesting and small scale irrigation development as a contribution towards agricultural development in the NEL Countries. NELSAP recently completed a project called Efficient Water Use for Agriculture Project (EWUAP). One of the recommendations of EWUAP was the need to develop Training/Dissemination materials on: *Adoption of low cost technologies for water storage, conveyance, distribution, treatment and use for agriculture that can be adapted by communities and households of the rural and peri-urbanpoor*. This Training Manual is the initiative of NELSAP, for that purpose.

Water harvesting is a suitable practice for utilising rain water and runoff flows for domestic and agricultural use. These techniques are widely used in many parts of the world, and the Nile Basin is no exception. Water harvesting interventions address water scarcity and improving the productivity of rainfall. They are methods which have been used since ancient times. Despite this fact, it is only within the last decade that African governments have considered supporting the use of water harvesting technologies in the region. Within the Nile Basin Countries, there is need for knowledge and training material for use by agricultural extension staff, many of whom did not receive the specialised technologies that are demanded by water harvesting. This Training Manual therefore meets this knowledge gap, in line with the aims of the NBI's Institutional Strengthening Project (ISP) and NELSAP's Subsidiary Action Program (SAP).

This Training Manual targets technical staff and middle level decision makers such as extension workers, managers and implementers of projects, researchers, development partners, public and private practitioners of agriculture in Africa. It is meant to inform, educate and enhance knowledge and practice as regards water harvesting for crop production in the NEL region. The information contained here may not be exhaustive and thus, readers are encouraged to seek further information from references cited in this publication and elsewhere.

Acknowledgement

The publication of this booklet was supported by the Nile Basin Initiative's NELSAP-RATP. RATP is a technical assistance project financed by CIDA. The author wishes to thank all the institutions and individuals who provided data/information for the publication of this manual. Special thanks go to Innocent Ntabana, Gabriel Ndikumana, Faith Livingstone, Francis Koome, Jean Jacques Muhinda, Adamu Zeleke, Habtu Bezabhe andMaibo Malesu among others. The views expressed here are not necessarily those of CIDA or NBI, as the content is solely the responsibility of the author.

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Glossary of Key Terms

Term	Definition/Brief description
Agriculture	Production, processing and marketing of crops and livestock from producer to consumer.
Arid	Very dry climate with less than 300 mm average annual rainfall, where cropping is possible only with support of water harvesting or irrigation.
Available water	The amount of water held in soil that plants can use.
Available water holding capacity	The total amount of water a soil profile can hold for plant uptake. It depends on soil depth, texture, structure and organic matter content.
Base-flow	That portion of water discharge of a stream contributed by ground water seepage and interflow
Contour (line)	An imaginary line joining all points of the same altitude above sea level on a land surface as represented on a map.
Cut-off drain	A ditch made to protect cultivated land from external runoff, normally with a gradient of 0.25-0.5%, also called diversion ditch.
Deep percolation	Downward movement/ seepage/ of water below the root zone under the force of gravity, eventually arriving at the water table.
Depression storage	Temporary holding of rainfall in hollows/basins and surface depressions.
Ephemeral stream	Flow which occurs for short duration, often in torrents, in a normally dry watercourse
Evaporation	A process in which water passes from liquid state to vapour state due to heat.
Floodwater harvesting	A water harvesting system using stream flow as its source of runoff. C:CA ratios very large.
Horizontal interval	The horizontal distance between two contour lines/ points on a land surface as represented on a map.
Infiltration	Absorption and downward movement/ seepage of rainfall into the soil.
Infiltration capacity	Limiting rate at which falling rain can be absorbed by a soil surface in the process of infiltration.
Interception	Catching and holding of rainfall above the ground surface by leaves, stems and residues of plants.
Interflow	Movement of soil water through a permeable layer in a down slope direction parallel with the ground surface, also called through flow.
Nitrogen-fixing	The ability of certain small organisms (bacteria, algae) to convert atmospheric nitrogen (a plant nutrient) into a form which can be used by plants. These organisms live near the roots of legumes.
Overland flow	Water flowing over a sloping ground surface to join a stream flow: a form of runoff.
Overtopping	Water flowing over the top of a bund or ridge, leading to erosion.
Percolation	Movement of water downward through the pores of the soil.
Perennial (crop).	A plant that lives for three or more years and which normally flowers and fruits at least in its second and subsequent years.

Term	Definition/Brief description
Rain fed agriculture	In rain fed agriculture, natural rainfall, which falls directly on a given field is the predominant source of water for growing crops, trees or pasture on that field. It also includes crops grown with flood flows harvested from excess rainfall runoff.
Salinity	Soils having high concentration of soluble salts. Salinity may be caused by the presence of salts in the soil or from irrigation water.
Sealing	When soil forms a sort of clay cement after rain, because the finest grains work their way into the soil pores. Also called clogging up.
Semi-arid	Fairly dry climate with average annual rainfall of about 300-700 mm, with high variability in rainfall.
Slope gradient	The angle of inclination of a slope, which may be expressed in degrees or as a percentage.
Soil moisture	Water held in the soil and available to plants through their root system, also called soil water.
Soil moisture profile	The depth to which water infiltrates into the soil, also called infiltration boundary
Spillway.	An outlet created in a retaining structure for allowing overflow of excess runoff.
Stream flow	Water that flows concentrated in a channel, watercourse, or valley. It includes both large and small channels e.g. a river, stream or gully
Sub-humid	A humid climate with average annual rainfall of roughly 700-1000 mm
Supplemental irrigation	Irrigation to ensure increased crop production in areas where rainfall normally supplies most of the moisture needed.
Surface runoff.	Excess rainfall which runs off the surface of the land, it includes both overland flow and stream-flow
Tillage	Preparation of the land for planting, or all the operations undertaken to prepare a seed bed in agriculture
Transpiration	Water that is taken up by plants from the soil and then lost to the air through small openings in the leaves of plants.
Vertical interval	Spacing between two structures determined on the basis of the difference in ground elevation, also referred to as vertical interval. Difference in height between two contour lines.
Vertisols	Black (sub) tropical soils with high clay content, developing deep, wide cracks when dry and difficult to till when wet.
Water harvesting	Activities whereby water from rainfall and/or surface runoff is collected, diverted, stored and utilized.
Water logging	State of land where the water table is located at or near the surface resulting in poorly drained soils, adversely affecting crop production
Water storage capacity	Maximum capacity of soil to hold water against the pull of gravity, also called field capacity.
Water table	Upper limit of the ground water.

1.
2.

INTRODUCTION

1.1. What are Drylands?

Drylands, sometimes referred to as "marginal rainfall areas" or arid and semiarid lands (ASALs) are areas with limited water resources. They are characterized by low, erratic rainfall, which varies from about 200 to 750 mm per year. Rainfall is unreliable and concentrated during a short rainy season with the remaining period tending to be relatively long dry spells or absolutely dry. Drylands have few rivers while the available ephemeral streams lack water during the critical dry season. Ground water may be unavailable, too expensive to exploit or of poor quality. Thus, water scarcity is a major feature of drylands. In Africa, drylands have traditionally been used for extensive livestock grazing, agro-pastoralism and production of certain drought resistant crops such as millet, sorghum and pulses. However, as population grows, agricultural expansion along with immigration of agrarian communities into drylands has led to increased cultivation of fragile environments. The result is declining soil fertility, land degradation, moisture stress and poor yields (Figure 1.1).

Figure 1.1 (a) Typical drylands are degraded and lack water *(Photos by Bancy Mati)*	**(b) A maize crop suffers moisture stress due to drought**

Drylands face great constraints for crop production. Yields vary enormously from year to year, and crops frequently fail due to drought. For farmers reliant on natural rainfall, it is extremely difficult to plan ahead and cropping is risky. The impacts of climate change have seen drought events get ever more frequent, being about every 2-5 years. The answer to sustainable crop production in the drylands increasingly lies in adoption of appropriate dryland farming techniques.

1.2 What is Dryland Agriculture?

Dryland agriculture, also referred to as dryland farming or dry farming, is the cultivation of crops without conventional irrigation, in regions of limited moisture (i.e. drylands), typically less than 500 mm of rain per annum. Dryland agriculture depends upon efficient storage of limited rainfall as moisture in the soil and the selection of crops and growing methods that make the best use of this moisture. These techniques are variously referred to as conservation agriculture as well as soil and water conservation (see Training Manuals 4 and 5). However, dryland agriculture can be upgraded by adoption of rainwater harvesting technologies, i.e. diversion, channeling and conservation of rainfall runoff. Water harvesting can be achieved through various techniques, many of which are low cost, affordable, utilizing locally available materials and offer sustainable solutions to make dryland agriculture more productive and profitable.

1.3 What is Rainwater Harvesting?

Rainwater harvesting (RWH) involves *collection, conveyance, conservation and storage of rainwater for various* *purposes (drinking water, livestock watering or agriculture).* It is the process of harnessing and improving the productive use of excess rainfall by turning surface runoff from a destructive element into an asset. Normally, rainwater is best collected where it falls, through *in-situ* conservation and/or channelling excess runoff water in a guided manner from catchment areas to storage reservoirs for various uses, especially for agriculture or stored in the soil profile for soil moisture replenishment.

Flood water harvesting refers to a variety of techniques for diverting and storing runoff in earth dams, sand dams, weirs, ponds and pans. It also includes runoff farming technologies (runoff harvesting, water spreading), where the harvested water is stored in the soil profile for growing plants. This enables crops to survive dry spells and to improve yields, even under insufficient rainfall.

1.4 What About Water Harvesting?

The term Water harvesting (WH) encompasses both rainwater harvesting and/or floodwater harvesting. The intermittent character of rainfall, runoff and floodwater flow requires some kind of storage, so that the water can be used later when needed. Thus, harvested water may be stored in tanks, cisterns or reservoirs or soil profile serves as a reservoir for a certain period of time. There are two basic types of runoff-farming systems:

(i) Supplemental water system, where the collected water is stored in some reservoirs and later used to irrigate a certain crop area (see Training Manuals 2 and 3).

(ii) Direct water application system, where runoff water is stored in the soil of the crop growing area during the precipitation – as described in this Manual.

A wide variety of water harvesting techniques for many different applications are known. Productive uses include provision of domestic and stock water, concentration of runoff for crops, fodder and tree production and less frequently water supply for fish ponds. In the context of this manual, the end use is crop production, including fodder and trees. This Training Manual describes water harvesting for plant production, variously referred to as runoff farming techniques.

1.5 What is Runoff Farming?

Runoff farming is simply rainwater harvesting for crop production. It is the process of concentrating rainfall as runoff from a larger area for use in a smaller target area. Runoff farming is also synonymous with "water harvesting for irrigation purposes". When the harvested runoff water from un-cropped areas is directed to a cropped area, this technique is called runoff farming. The soil profile acts as a water storage container, but storage in ponds or cisterns is also feasible. Runoff farming is distinguished from conventional irrigation by three key features:

(i) The catchment area is contiguous with the runoff receiving area (called run-on area, or cropped area, or cultivated area), the latter being relatively small;

(ii) Water application to the cropped area is essentially uncontrolled, the objective is simply to capture as much runoff as possible and store it within reach of the plant roots, in the soil profile of a cultivated area, and

(iii) Water harvesting can be used to concentrate rainfall for purposes other than crop production.

Table 1 provides an overview of the various water harvesting techniques forms and their suitability features.

Table 1. Overview of the main types of water harvesting systems

WH-type	Kind of flow	Kind of surface	Size of catch-ment	Catch-ment: cropping area ratio	Water stor-age type	Water use
Roof top wa-ter harvesting	Sheet flow	Roofs of all kinds	Small		Tanks, jars, cisterns	Drinking, domestic, livestock
Water harvest-ing for animal consumption		Treated ground surfaces	>3 ha	Extreme various	Tanks, cis-terns	Livestock
Inter-row WH		Treated Ground surfaces	1-5 m²	1:1 – 7:1	Soil profile (reservoirs, cisterns)	Tree, bush, vegetable and field crops
Microcatch-ment WH	Sheet and rill flow	Treated and untreated ground surfaces	2-1000 m²	1:1 – 25:1	Soil Profile (reservoirs, cisterns)	
Medium-sized catchment WH	Turbulent runoff/chan-nel flow	Treated and un-treated Ground surfaces	1000 m² - 200 ha	10:1 – 100:1	Soil Profile (reservoirs, cisterns)	
Large catch-ment WH	Flood water flow	Untreated ground surfaces	200 ha – 50 km²	100:1 – 10,000:1	Soil profile	

Source: Prinz, D. 1996. Water harvesting -, past and future

1.6 The Case for Runoff Farming

Runoff farming or rainwater harvesting for crop production, is applied in arid and semi-arid regions where rainfall is either not sufficient to sustain a good crop and pasture growth or where, due to the erratic nature of precipitation, the risk of crop failure is high. Water harvesting can significantly increase plant production in drought-prone areas by concentrating the rainfall/runoff in parts of the total area.

Runoff farming is an ingenious way of improving the productivity of rain fed agriculture in dry regions where conventional methods are unreliable. The method should be considered in regions where rainfall is inadequate or unreliable and normal rain fed farming has become a risky venture.

The goals of runoff farming include:

- Restoring the productivity of land which suffers from inadequate rainfall.
- Increasing yields of rain fed farming
- Minimizing the risk in drought prone areas
- Combating desertification by tree cultivation

In areas with an annual precipitation between 100 and 700 mm, low cost water harvesting might provide a workable alternative if irrigation water from other sources is not readily available or too costly. In areas with more than 600 - 700 mm annual rainfall, water harvesting techniques can prolong the cropping season. In comparison with pumping water, water harvesting saves energy and maintenance costs.

1.7 Advantages of Runoff Farming

Runoff farming helps crops by providing extra moisture at different stages of growth - although timing cannot be controlled. The following are some of the advantages:

(i) direct economic benefit from increased crop production,

(ii) reduces the volume of surface flows, helping to control soil erosion, helping overcome problems of low amounts and/or poor distribution of rainfall,

(iii) the techniques are easy to design and adapt to different situations,

(iv) Runoff farming techniques are relatively affordable, and utilize local resources

(v) significant volumes of water can be stored at catchment scales leading to ground water recharge,

(vi) Helps tree and pasture establishment, thus control of desertification, facilitating environmental conservation and climate change mitigation.

(vii) Runoff farming provides extra moisture which can make a significant difference during:

- the time of sowing when germination and establishment can be improved;
- when a dry spell threatens crop growth at mid-season, and
- while the crop is at the vital stages of flowering and grain filling.

Thus, runoff farming is a viable alternative for crop production in the drylands, when irrigation water from conventional sources is not readily available or too costly.

1.8 Limitations of Runoff Farming

Runoff farming faces many constraints which discourage farmers from adopting the techniques. Some of the most common ones include:

(i) Runoff farming systems are reliant on rainfall, hence they still carry a risk of failure if rainfall fails or is excessive.

(ii) The collection and concentration of runoff takes place during the rainfall event, and if missed, the whole system may not function.

(iii) Runoff farming systems require the catchment area to be impervious, with high runoff producing properties and the adjacent cropped area to have deep soils which hold moisture. This combination is difficult to achieve.

(iv) High evaporation and deep percolation losses are common problems in most runoff harvesting systems.

(v) Many runoff farming techniques have high labour requirements, which can be a constraint among poor and marginalized communities,

(vi) Some of the structures constructed for runoff farming are temporary and must be re-built each rainfall season.

(vii) A good technical background in water/engineering is sometimes necessary to design structures or solve problems when they arise, and such capacity may be lacking.

3. DESIGN OF RUNOFF HARVESTING SYSTEMS

2.1. Basic Arrangement of a Rainwater Harvesting System

A runoff harvesting system is based on the utilization of surface runoff combined with natural rainfall, to grow crops. Therefore, the system requires a runoff producing and a runoff receiving area (run on area).

In most cases, with the exception of floodwater harvesting from far away catchments, water harvesting utilizes the rainfall from the same location or nearby area. Water harvesting projects are generally local and small scale projects. Moreover, runoff farming does not necessarily depend on high technology, although it does require expertise, primarily for evaluating site suitability and in designing the system.

In runoff farming, there is deliberate collection of rainwater from a surface (called a catchment) and its conveyance to a cropped area, whose relationship is as shown in Figure 2.1.

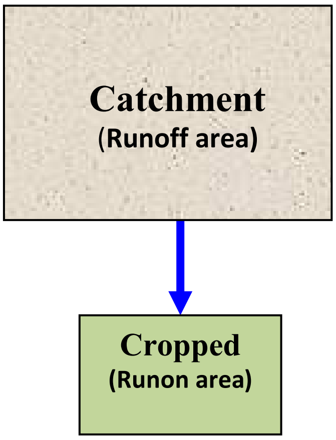


Figure 2.1 Simple illustration of a runoff harvesting system for crops

A runoff farming system has four stages:

(i) rainfall induces surface flow on runoff areas,

(ii) at the foot of slopes, runoff collects in basin areas,

(iii) most of the water infiltrates and is stored in the root zone, and

(iv) After infiltration has ceased, the stored soil water is conserved.

The design of runoff farming systems has the following requirements:

The design of water harvesting systems for crop production requires that certain data be made available. The following factors regarding the site; its climate, especially the seasonal rainfall amounts and intensities, the soil types (physical and chemical properties), the topography as the land should neither be flat nor too steep, the crop types, available labour, levels of mechanization and socio-economic factors. For rainwater-harvesting to be possible, three basic landscape elements must be present:

(i) The landscape surface or soil conditions must be able to produce runoff,

(ii) The landscape surface must include variations in elevation so that runoff water created during rains will flow into and be collected by cultivated areas, and

(iii) The collection areas (cropped area) must have adequately deep soil horizon of a suitable structure to store sufficient runoff for crop production.

These factors affect the choice of method and opportunity for success.

2.2 Rainfall-Runoff Characteristics

In water harvesting, rainfall-runoff characteristics are very important. In general, statistical methods are used to determine the probability of a storm of a given return period, so as to design a structure of adequate capacity. As runoff generation is also a function of the catchment, various methods can be used such as the SCS curve number method or the Runoff coefficient methods.

The most suitable areas for runoff farming are those with an average of 300 - 600 mm annual rainfall which comes in relatively intensive rainstorms. In designing a runoff harvesting system, the crop-water demand should be met by the total water obtained from the natural rainfall plus that harvested runoff as follows:

Crop water requirement = Rainfall + Runoff

The aim of a water harvesting design is therefore to estimate the catchment area required or a given crop area so that a crop gets sufficient moisture to produce the needed crop

Design Rainfall

The design rainfall (R) is calculated for a certain probability of occurrence. In the absence of long term data, a 67% probability value is assumed. This simply means rainfall amount that was recieved or exceeded in two out of three years.

Selecting design rainfall level

The selection of design rainfall is very important. The objective is to select a seasonal rainfall value that best suits a design. A short return period storm is the most frequent; hence it has a high probability. Technically, the selection of such a rainfall level enables a design which should work at all longer return periods. However, such rainfall levels result in very large catchments and are therefore impractical as they waste land. On the other hand, a very long return period is not useful. The amount of rainfall is very high, which is a rare occurrence in most African countries. The designed catchment can end up being too small and could fail to raise a crop in most of the years. A balance between the two extremes is clearly desired. The selected rainfall level depends on better technical information regarding the crop based on discussions with local people since climatic data may not be available.

Estimating the runoff coefficient

Runoff coefficient is a measure of the proportion of rainfall that becomes surface runoff. It is a function of the rainfall as well as the catchment characteristics discussed above. Runoff coefficient factor (K) can be calculated using annual rainfall or seasonal rainfall as follows:

Runoff coefficient (K) =	Annual (seasonal) total runoff
	(Annual (seasonal) total rainfall

Generally, two years data can be used for this calculation. Otherwise, in most drylands of Africa, experience has shown runoff coefficients (K) ranges 0.1 to 0.5, but the value could be up to 0.7 for bare crusting soils under intense storms.

2.3 Catchment Characteristics

A water harvesting system consists of two areas - a *cropped* and a *catchment* area (see figure 2.1). A cropped area is where a crop is planted and gets its moisture and nutrients. A catchment area is used to provide additional soil moisture in form of runoff. The catchment for a runoff harvesting system should be gently sloping and as impervious as possible. It may be necessary to compact the catchment area, or use roads, rocky surfaces, home compounds and open fields for larger flows in external catchments. The soils of the catchment area should have low permeability in order to release more runoff. The catchment should be free of crops and weeds. Research has shown that bare compacted ground can yield as much as 50% runoff. The runoff area (catchment) should show a sufficiently high run-off coefficient and if possible, it should be impermeable. The more arid an area is, the larger the catchment area should be in relation to the cropping area for the same water yield. Runoff farming in a small watershed can also be done for larger cropped fields in macro-catchment systems.

2.4 Crop Selection

Runoff harvesting is applicable to most crops, except those which suffer water-logging. Thus, runoff harvesting can be applied to field crops, trees, vegetables or pasture. In general, quick maturing varieties (drought evading) and drought resistant varieties are recommended. In Sub Saharan Africa, the most common cereal crops grown under runoff farming include:

- Sorghum (*Sorghum bicolor*) is the most common grain crop under water harvesting systems. It is a crop of the dry areas, and in addition to its drought adaption, it also tolerates temporary water-logging - which is a common occurrence in some water harvesting systems.

- Pearl Millet (*Pennisetum typhoides*) is grown in drier areas of Africa and apart from being drought tolerant, it matures rapidly.

- Maize (*Zea mays*) is also grown under water harvesting but is neither drought adapted nor water-logging tolerant - but in parts of East and Southern Africa maize is the preferred food grain, and farmers are often reluctant to plant millet or sorghum.

- Legumes are less frequently grown under water harvesting but should be encouraged because of their ability to fix nitrogen and improve the performance of other crops. Suitable legumes are Cowpeas (*Vigna unguiculata*), green grams (*Vigna radiana*), lablab (*Lablab purpureus*), and groundnut (*Arachis hypogea*). All are relatively tolerant of drought and are fast maturing.

- Runoff harvesting is used to establish tree seedlings in dry areas, by concentrating water around the seedlings. This can make considerable difference to tree survival at this vital early stage.

Other crops are also grown with runoff harvesting, such as vegetables, sweet potatoes, fruit trees e.g. mangoes, bananas, papaya and pastures and forest trees. Typical crop water requirements for these crops under tropical conditions are presented in Annex 1.

2.5 Characteristics of the Cropped Area

The cropped area should have deep soils and of high permeability. The soils should not be saline or sodic. In many systems, cropped area comprises planting pits of various types, earth bunds, or other structures that optimize infiltration and moisture storage. The "run-on" area, where the accumulated water is stored and/or utilized, should have a high infiltration rate a high storage capacity, which depends on soil texture, organic matter content and general soil structure, a sufficient soil depth (> 1m). The water retention capacity has to be high enough to supply the crops with water until the next rainfall event.

Crop water requirement

Crop water requirement (CWR) is a measure of the amount of water a plant takes to grow and produce. This value is usually expressed as a function of evapotranspiration, i.e. the sum total of evaporation from the land and transpiration by the plant (ET_{CROP}), calculated as follows:

$$ET_{CROP} = K_C \times ET_O$$

ET_{CROP} = The water requirement of a given crop in mm per unit time (mm/day, mm/year, mm/month, mm/season)

K_C = Crop factor

ET_O = The "Reference crop evapotranspiration" in mm per unit time (mm/day, mm/year, mm/month, mm/season)

Estimating the Efficiency Factor

This efficiency factor (E)is a function of how well the harvested water is used by the plant. It is used because not all water put in the root zone is used by the plant. The factor varies greatly from season to season. Low rainfall seasons have high efficiency values because there may be very limited deep percolation. In the design of surface irrigation systems, an efficiency factor of 0.4-0.85 is commonly used. Runoff farming therefore increases the amount of water available to meet the crop water requirement, and evaporation losses should be reduced as much as possible.

2.6 Source of Runoff

Systems in which the source of runoff is close to the cropped area are known as *within-field systems*. In systems where runoff comes from a different area, they are known as *external catchment* systems. In general, within-field systems are also *microcatchment* systems, while external catchment systems usually are *macrocatchmen*t in nature. In designing runoff farming, the source of runoff is important as it affects the selection of crop as well as the method to adopt.

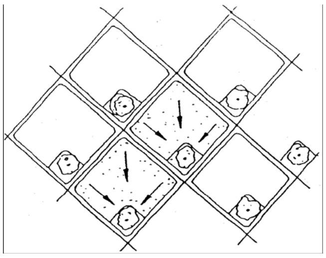
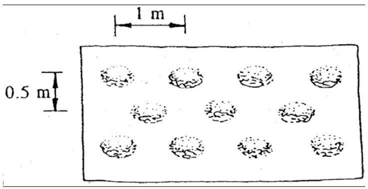
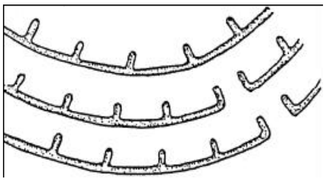
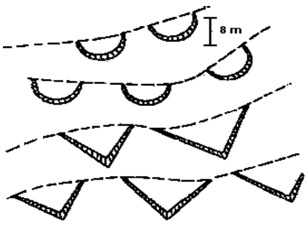
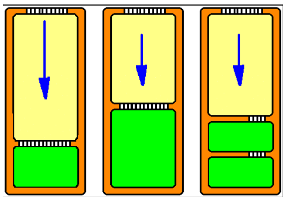
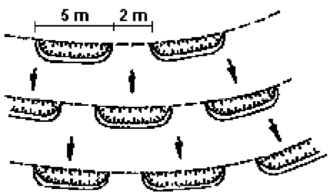
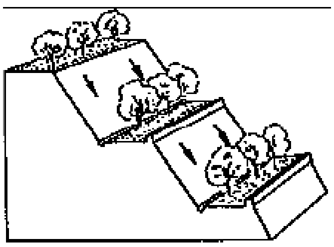
2.7 Design of Catchment to Cultivated Area Ratio

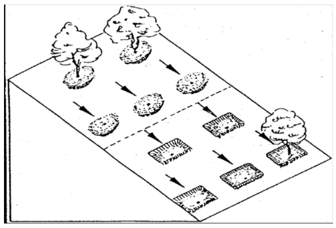
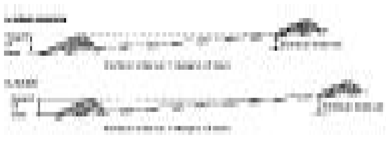
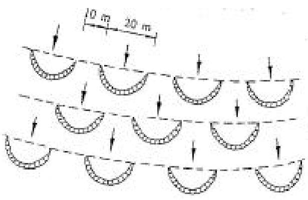
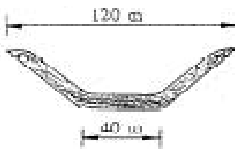
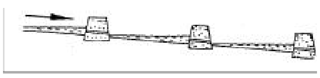
Each runoff harvesting system consists of a catchment (collection) area and a cultivated (concentration) area. The ratio of catchment-to-field can range from 1:1 and from 1.0 to many square kilometres in size according to micro- or macro-catchment or floodwater runoff farming system. Rainfall is normally not enough to meet crop water requirement. The amount of water harvested should be equal to the extra water required by a crop. This is influenced by the runoff coefficient and the amount of rainfall received. Because some water entering the soil is inevitably lost through deep percolation, an efficiency factor (E) is considered. The catchment (C) and the cropped areas (CA) are related by the catchment to cropped area ratio (C/CA) which is estimated as follows:

Catchment area (C)_		Crop water requirement (CWR)– Design effective rainfall (R)___
Cultivated area (CA)		Design rainfall (R)x Runoff Coefficient (K) x Efficiency factor (E)

Most runoff farming techniques are designed based on this equation. The design may be modified to take care of farm size and various crop spacing. General guidelines for selection of the C/CA ratio, allowable slope gradient and rainfall requirements are provided in Table 2.

Table 2. Basic design criteria of various runoff farming techniques

Type	Illustration	Parameters
Negarim		C= 3 – 250 CA= 1 - 10 C/CA= 3 : 1 - 25:1 PREC= 150 - 600 mm/a SL = 1 - 20%
Pitting		C= 0.25 CA= 0.08 C/CA= 3:1 PREC= 350 - 600 mm/a SL= 0 - 5%
Contour ridges		C= 100 CA= 20 C/CA= 5:1 PREC= 300 - 600 mm/a SL= 5 - 25%
Semi-circular hoops/demi-lunes & Triangular bunds		C= 24-226 CA= 6-57 C/CA= 4:1 PREC= 300 - 600 mm/a SL= 2 - 20%
Meskat-type		C= 500 CA= 250 C/CA= 2:1 PREC= 200 – 600 mm/a SL= 2 - 15%
Valleranitype (fully mechanized)		C= ~ 15 CA= ~ 2.4 C/CA= 6:1 PREC=100 – 600 mm/a SL= 20 - 50%
Contour bench terraces		C= ~2-16 CA= 2-8 C/CA= 1:1-8:1 PREC= 100 – 600 mm/a SL= 20 - 50%

Type	Illustration	Parameters
Eye brow terraces; Hill slope micro-catchments		C= 5 – 50 CA= 1 - 5 C/CA= 3:1 - 20:1 PREC= 100 – 600 mm/a SL= 1 - 50%
Stone dams		(extreme variations) PREC= 300 – 600 mm/a
Large semi-circular hoops		C= 750 - 10,000 CA= 50 - 350 C/CA= 15:1 - 40:1 PREC= 200 -400mm/a SL= 1 - 10%
Trapezoidal bunds		C= 5 - 3 x 105 CA= 3,500 C/CA= 15:1 - 100:1 PREC= 200 – 400 mm/a SL= 1 - 10%
Hillside conduit systems		C= 10 - 107 CA= 1 - 105 C/CA= 10:1 - 100:1 PREC= 100 – 600 mm/a SLC= > 10% SLCA= 0 - 10%
Liman terraces		C= 2x104 -2x105 CA= 1,000 - 5,000 C/CA= 20:1 - 100:1 PREC= 100 – 300 mm/a SL= 1 - 10%
Cultivated reservoirs		C= 1,000 -10,000 CA= 100 - 2,000 C/CA= 10:1 - 100:1 PREC= 150 - 600mm/a SLC = > 10% SLCA = 0 - 10%

Adapted from: Prinz, D. 1996. Water harvesting, past and future

<u>Legend</u>:

C = Catchment size (m^2)
PREC = Precipitation
CA = Cropping area (m^2)
SL = Slope
C/CA = Catchment: Cropping Ratio
SLC= Slope of catchment area

SLCA= Slope of cropping area.

2.8 Design of Runoff Control and Retaining Structures

Two types of embankments are used in water harvesting i.e. stone and earth bunds. Stone bunds are porous and can allow some overtopping. When loose stone is available, it should be preferred to earth bunds. Stones can be used together with grass; this helps to slow runoff and deposit suspended soil while allowing the water to slowly flow down the land slope. Soil is the most abundant construction material. Earthen bunds are made by spreading the soil in uniform layers and compacting at optimum moisture until the required height is achieved. For field conditions, the most practical construction period is when the soil is moist, such as immediately after harvesting the crop; after a few showers at the beginning of the main season; or during minor rainy events.

2. 9 Safety Features

As runoff harvesting involves handling excess flows, overflow arrangements are usually necessary to prevent failure by overtopping. In most cases, the structures can be designed with a return period of 10 years. However, spillways are usually provided in most structures, or a generous freeboard provided where maximum impoundment is desired.

2.10 Soil Fertility and Agronomic Practices

Dry environments tend to have soils of low organic matter and hence poor for agriculture. Thus, soil fertility is usually the second most limiting production factor after moisture stress. The improvement in water made available to plants under water harvesting can further lead to depletion of soil nutrients. Agronomic methods of **soil fertility management** such as crop rotation are usually encouraged. Legumes should be alternated with cereals as often as possible. Intercropping of cereals with legumes - sorghum with cowpeas for example, can also lead to higher overall yields as well as soil fertility maintenance. It is very important to maintain levels of **organic matter** by adding animal manure or compost to the soil. Inorganic fertilizers can also be used but with soil testing and considerations of the physical and economic impacts based on the crops grown.

Weeds are a problem where water harvesting is used, due to the favourable growing conditions where water is concentrated. Weeds are especially a problem at the start of the season and therefore early weeding is extremely important.

Planting early during the rainfall season is a good agronomic practice, as the crop makes best use of limited rainfall. In some areas it may be best to do "dry planting", meaning to plant seeds before the rains arrive. Opportunistic or "take-a-chance" planting of a quick legume crop like cowpeas can make use of late season or out of season rainstorms.

Runoff farming systems perform better when plant populations are less than conventional (i.e. **wider crop spacing**), so as to reduce competition for limited soil moisture. This improves plant survival in case of moisture stress and can improve yields in low rainfall zones.

2.11 Selection of Appropriate Runoff harvesting System

There are very many types of structures that can be made to facilitate runoff harvesting for crop production. The structure's name is based mostly on the shape and function, particularly of the cropped area. The commonly applied forms of water harvesting can be grouped into six categories. These include a) roof top water harvesting, b) surface flows water harvesting, c) inter-row water harvesting, d) microcatchment water harvesting, e) medium-sized/external catchment water harvesting, f) large catchment (floodwater) systems. Figure 2.2 shows various types of water harvesting systems.

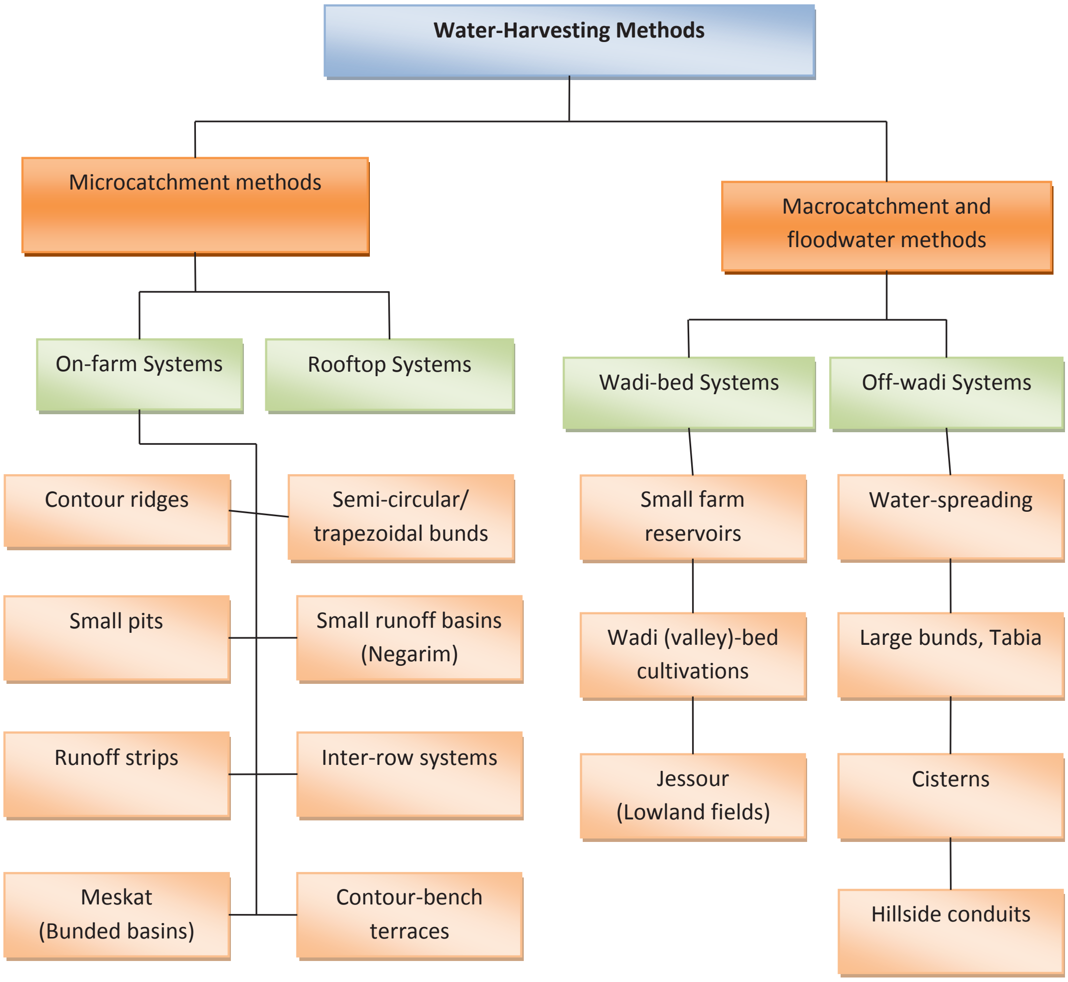


Figure 2.2 Classification of rainwater harvesting methods for crop production
Source: Oweis et al., 2001. Water harvesting: Indigenous knowledge for the future of the drier environments

2.12 Basic Categories of Runoff Harvesting Systems for Plant Production

Water harvesting systems for crop production (runoff farming techniques) fall under three basic categories as follows:

- Microcatchments rainwater harvesting (within-field) systems
- External catchment rainwater harvesting systems
- Floodwater farming (floodwater harvesting).

Each of these categories can further be sub-divided into the actual technologies and practises adopted by farmers, whose details are presented next in Chapters 3, 4 and 5.

3. MICROCATCHMENT RUNOFF HARVESTING SYSTEMS

3.1 What are Microcatchment Systems?

Microcatchment runoff farming systems (microcatchment rainwater harvesting, or within-field water harvesting systems) include structures such as basins, pits, bunds and other water harvesting systems that get their runoff from small areas.

Microcatchments are normally **within-field systems** since runoff comes from within the vicinity of the cropped area, where overland flow harvested from short catchment length and the runoff stored in the soil profile (Figure 3.1). In design, a small portion of upslope land is allocated for runoff collection, which is "harvested" and directed to a cultivated area (run-on area or cropped area) down slope. The runoff within a field is directed either to single plants e.g. fruit trees, or to clusters of plants or row crops e.g. maize, sorghum or groundnuts.

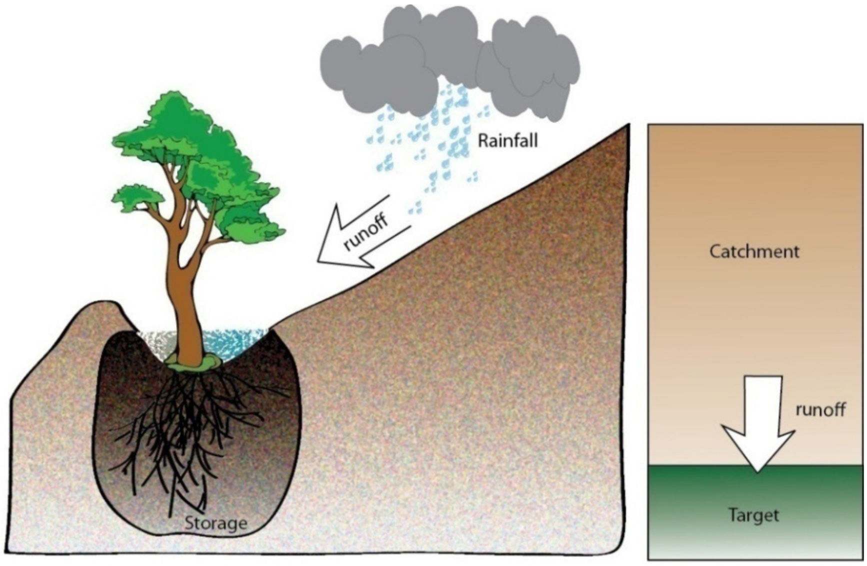


Figure 3.1 Schematic representation of a microcatchment runoff farming system

The arrangement of the run-on/cropped areas is such that alternating catchment and cropped areas often follow the contours. Compaction and removal of weeds from the catchment area helps to reduce infiltration and increase runoff. In the cultivated/run-on area, pitting, basins, deep tillage and loosening the soil is done to increase infiltration.

Under microcatchment systems, the catchment can range from 1 - 30 metres long. 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 is normally no provision for overflow since the catchment area is small. Research in certain semiarid areas has shown that it is possible to increase yields of most crops by 30–90% from microcatchment water harvesting. Typical Examples include, zai pits,Negarim microcatchments (for trees), contour Bunds (for trees), contour Ridges (for crops), semi-Circular Bunds (for range and fodder).

Advantages of Microcatchment RWH systems

They are simple in design, low-cost and relatively easy to install since they mostly require just manual labour. Therefore microcatchment systems are easily replicable and adaptable. Within-field systems also tend to require less mechanization, relying more on manual labour and animal draught. They also achieve a higher runoff efficiency than large scale water harvesting systems, with almost no conveyance losses and plant growth is usually even. Microcatchment systems carry elements of erosion control, thus conserve both water and soil nutrients. Most types of microcatchment systems can be constructed on almost any slope, including almost level plains, and there are designs to suit a wide range of crops, trees and fodders.

Limitations of Microcatchment RWH systems

Runoff farming requires relatively large labour inputs and land requirements. It also utilizes more land than conventional cultivation because the catchment area is sometimes removed from potentially arable land, especially in microcatchment systems. The catchment area has to be maintained, i.e. kept free of vegetation which requires a relatively high labour input. If overtopping takes place during exceptionally heavy rainstorms, the systems may collapse affecting other crops and structures downhill. Runoff farming requires that crops are planted with relatively wider spacing or structures are spread out, resulting in low crop densities and hence lower yields per unit area, in comparison with conventional cropping systems.

Types of Microcatchment systems

Microcatchment systems can be classified into five groups as follows:

a) Earth bunding systems/basins
b) Stone bunding
c) Pits (pitting systems) and

Within each classification are several techniques, each of which is described below:

3.2. Earthen Bunding

Earthen bunds are various forms of earth-shaping, which create run-on structures for ponding surface runoff, mostly designed as within-field water harvesting systems. They are suited to smallholder farms and where there is no opportunity for tapping water from an external catchment. In design, the soil bunds are aligned along the contour, with spillways at 20 m intervals to control the application of surface water in each bund-section where the crop is cultivated.

There should be a deliberate effort to distinguish bunds meant for within-field water harvesting and those meant for conventional soil and water conservation. When earth bunds are used for runoff harvesting, 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. The salient feature in bunding is that the crop is grown in the furrow, while the earth bund acts as an embankment to hold and retain more water. Examples of earthen bund systems are presented below.

3.2.1 Contour Ridges

Contour ridges, sometimes known as contour furrows or micro-watersheds, are small, ridge-and-furrow earthen bunds made along the contour. They are essentially a within-field water harvesting system for small-scale production of crops, particularly cereal grains (Figure 3.2). The objective of the system is to concentrate local runoff and store it in the soil profile, close to the plant roots. A cereal crop can be intercropped with a pulse, by planting the legume slightly upslope of the cereal but within the ponding area of the furrow. The most commonly used crops are maize, sorghum and millets, while short legumes such as cow peas, green grams, beans and ground nuts can also be grown.

Design features

In design, contour ridges consist of parallel, or almost parallel, earth ridges approximately on the contour rising about 0.15-0.40 m height and spaced around 2 to 20 m apart, depending on slope, soil surface treatment. Soil is excavated and placed down slope to form a ridge, and the excavated furrow above the ridge collects runoff from the catchment strip between ridges. Small earthen ties are made within the furrow at a spacing of about 4.0 to 5.0 m to prevent lateral flow. A diversion ditch may be necessary to protect the system against runoff from outside. The surface runoff is collected from the uncultivated strip between ridges and concentrated in the furrow just above the ridges, where a crop is grown.

Contour ridges are suited to areas receiving about 350 - 750 mm of rain per annum. They can be practised on nearly all soil types, all soils which are suitable for agriculture, but clayey soils with good water retention properties are preferable. Very sandy soils tend to silt up soon and are not advisable for this system. The farmland should be almost flat to very gently sloping and not exceeding 5.0% slope. The land topography should be even and areas with hills or rugged terrain should be avoided.

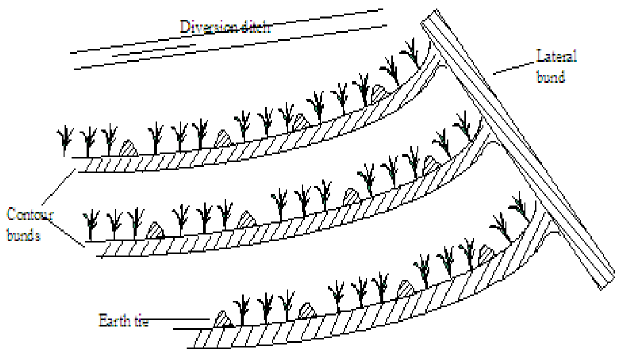


Figure 3.2 (a) Contour earth bunds for runoff farming with field Crops	**(a) Contour earth bunds with maize crop** *(photo courtesy of MoARD, Ethiopia)*

Catchment: cultivated area ratio

The cultivated area is the strip, about a 50 cm wide within the furrow area. Crops are planted in this space where they make use of the runoff concentrated in the furrow. The calculation of the C:CA ratio follows the design equations described in Chapter 2. In practice, assuming a spacing of 1.5 - 2.0 metres between ridges, the C:CA ratios range about 2:1 to 3:1 respectively for annual crops in semi-arid areas. In this system, the ridges are made as high as is necessary to prevent overtopping by runoff. As the runoff is harvested only from a small strip between the ridges, a height of 15 -20 cm is sufficient. If bunds are spaced at more than 2 metres, the ridge height must be increased.

Advantages

The contour ridge system is simple to construct. Construction can be by hand or by machine. It generally is less labour intensive than conventional tillage. This is because the "catchment strip" that lies ahead of the furrow is left uncultivated, and if possible, compacted so as to generate more runoff. The yield of runoff from the very short catchment lengths can be quite efficient. When designed and constructed correctly, there should be no loss of runoff out of the system, and therefore, no need for spillways. Another advantage is attaining even crop growth because each plant receives runoff from roughly the same size of catchment area.

Limitations

Contour ridges are limited to areas with relatively high rainfall, as the amount of harvested runoff is comparatively small due to the small size of the catchment area. Contour ridges for runoff harvesting are not yet a widespread technique in the region. This is due to the need for leaving a strip uncultivated within the farmland, which some farmers find difficult to accept. Also, the system has to be re-constructed each crop season as it silts up easily.

3.2.2 Inter-row water harvesting

Inter-row water harvesting, is a type of microcatchment technique similar to contour ridges but without the ties. Thus the rows tend to be relatively straight or curved along the contour (Figure 3.3). They are used for field crops planted into one or two rows. The inter-row space acts as the "microcatchment area" and it runs parallel to the crop rows

Design features

Inter-row water harvesting is suited to flat terrain or on gentle slopes of up to 5 %. The soils should be at least 1 m deep, while annual rainfall should not be less than 200 mm/year. On flat terrain (0 - 1 % inclination), short earthen bunds are constructed and compacted if possible to increase runoff. The catchment to the cropping ratio (C:CA) varies from 1:1 to 5:1, depending on available runoff amounts. The bunds are about 0.15 m – 0.2 m in height and spaced at about 1.0 to 2.0 metres. The catchment area should be weeded and compacted. Land preparation for inter-row water harvesting can be by hand or machine.

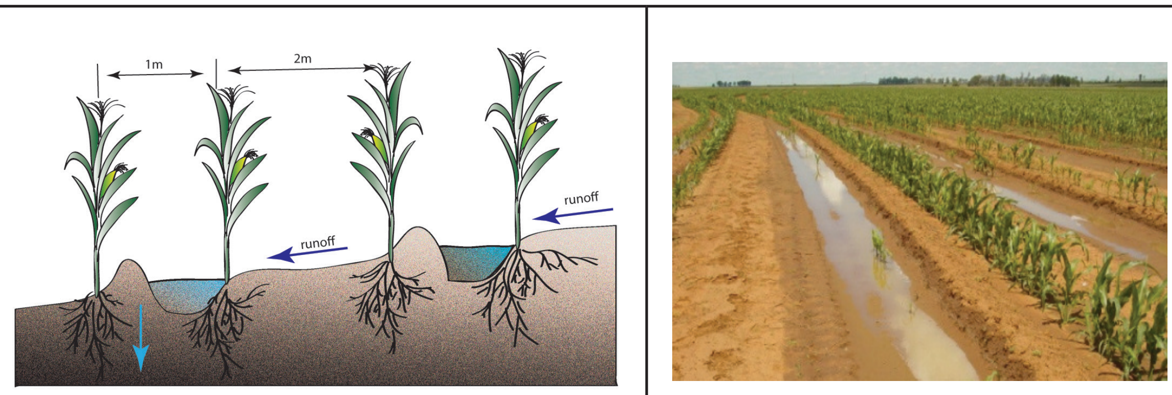


Figure 3.3 (a) Sketch of inter-row water harvesting **(b) Maize with inter-row water harvesting** *(photo courtesy of Leon van Rensburg)*

Limitations

Inter-row water harvesting is not suited for sloping land, unless for areas with a known regular rainfall pattern. This is because very high rainfall intensities may cause breakages of the bunds.

3.2.3 Runoff strips

Runoff strips is a method of inter-row water harvesting, but the strips hold more than one or two crop rows. The farm is divided into strips along the contour. The method is used to support field crops in drier environments where production is risky and yields are low. This technique is recommended for cultivation of cereal crops such as wheat, barley and other field crops in large scale farming.

Design features

In runoff strip cropping, the crops are planted in rows that run along a contour (Figure 3.4). The strip uphill is uncultivated and compacted to act as a catchment while a downstream strip supports crops. The downstream strip should not be too wide (1 -3 m), while the catchment width is determined in accordance with the amount of runoff water required. The same cropped strips are cultivated every year, but clearing and compaction may be needed to improve runoff.

Runoff strip cropping is suitable for gentle slopes. The technique can be fully mechanized and needs only a relatively low input of labour. It works better with land levelling to ensure that water distribution is even along the length of the strip.

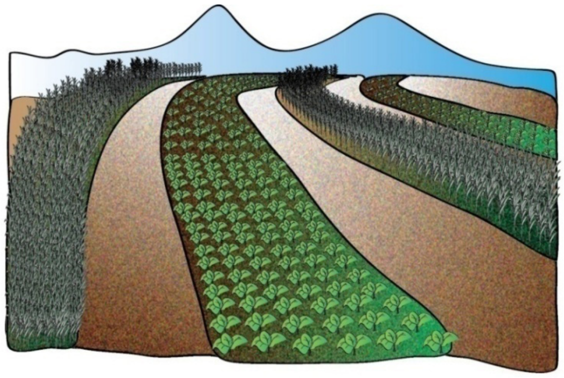



Figure 3.4 (a) Sketch of runoff strip cropping

(b) Inter-row water Hharvesting with bean crop*(photo by Bancy Mati)*

Advantages

Runoff strip cropping performs well under good management. The continuous cultivation of the cropped strip can build up soil fertility and improve soil structure, making the land more productive. The catchment area can be used for grazing after the crop has been harvested.

Limitations

One problem with runoff strip cropping, however, is that the distribution of water across the strip may not be uniform. This happens especially on gentle slopes when the cropped strip is too wide.

3.2.4 Contour earth bunds for trees

Contour earth bunds for trees are a simplified variation of contour ridge system but designed specifically for tree crops. They are basically microcatchment systems, comprising small ridges at least 20 cm high. The spacing between ridges is wider, at least 3.0 m apart, to accommodate the tree crops and a small catchment as source of runoff. The furrow with small earth ties to retain the water and reduce lateral flow. Along the furrow, pits are dug at the recommended tree spacing, and the trees planted within. Runoff from the catchment area is ponded in these pits while the ridge prevents any excess from overflow (Figure 3.5). Unlike ordinary terraces, the tree crop is grown in single rows in the furrow leaving the rest of the land uncultivated as a catchment area.

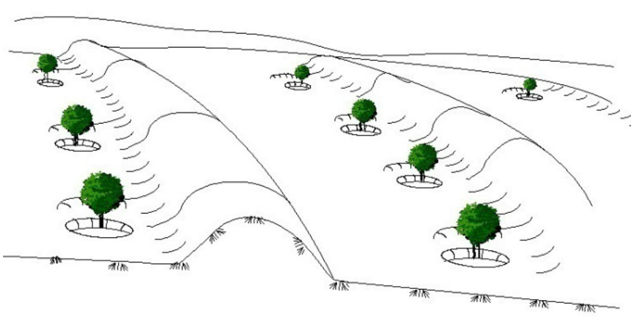


Figure 3.5(a) Contour earth bunds for trees | **(b) Contour earth bunds with trees** *(photo courtesy of Donald Gabriels)*

3.2.5 Semi-circular bunds

Semi-circular bunds (also known as demi-lunes or crescent-shaped bunds) involve making earth bunds in the shape of a semi-circle with the tip of the bunds on the contour. They are suitable for arid and semi arid areas where annual rainfall ranges about 200 - 750 mm. The land terrain should be even, with topography that is almost flat to gently sloping. Slope steepness should be less than 2%, but modified bund designs of up to 5% slopes are allowed.. Semi-circular bunds can be constructed in a variety of sizes, with a range of both radii and bund dimensions. Small radii are common when semi-circular bunds are used for tree growing and production of crops. Three types of semi-circular bunds can be distinguished:

(i) Semi-circular bunds for annual crops
(ii) Semi-circular bunds for trees
(iii) Semi-circular bunds stabilized with stones.

3.2.6 Semi-circular bunds for trees

In Eastern Africa, semi-circular bunds are commonly made for rangeland rehabilitation for the establishment of young trees in semi-arid areas.

Design features

In design, the bund is made with a radius ranging from 3 m to 6 m facing upslope. The bund height is normally 0.25 m high. The side slopes are normally 1:1 which result in a base width of about 0.75 m at a selected top width of 0.25 m. The tips of each bund are set on the contour, and a recommended radius for these smaller structures is 2 to 3 metres, with bunds of about 25 cm in height. The distance between the tips of adjacent bunds in the same row is 3 metres. Bunds in the row below are staggered, thus allowing the collection of runoff from the area between the bunds above. The distance between the two rows, from the base of bunds in the first line to tips of bunds in the second, is 3 metres. At this spacing 70-75 bunds per hectare are required. A hole of about 0.6 m diameter and 0.6 m deep is dug at the lowest end of the bund. The sub-soil excavated from the pit is used to build up the earthen bund in the shape of a semi-circle (or half-moon) around the hole. The excavated planting pits are filled with a mixture of organic manure and topsoil to provide the required fertility and also to help retain the moisture. Then the tree seedling planted in the hole. The runoff water is collected in an infiltration pit at the lowest point of the semi-circular bund, where the seedlings are planted. The field arrangement is in alternate rows to allow the excess runoff from one bund to flow into the next (Figure 3.6).

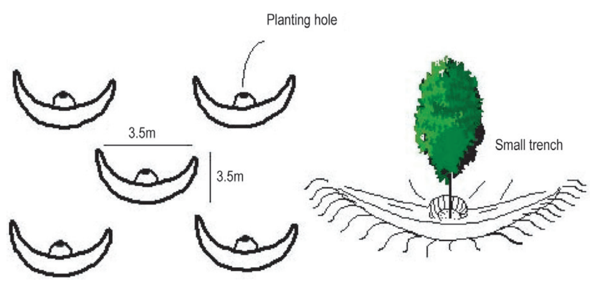


Figure 3.6 (a) Semi-circular bunds for tree crops	**(b) Making semi-circular bunds for trees** *(photo courtesy of Donald Gabriels)*

Catchment: cultivated area ratio

The C:CA ratios of up to 3:1 are generally recommended for semi-circular bunds with water harvesting systems used for rangeland improvement and fodder -production. The reasons for applying low ratios are that already adapted rangeland and fodder plants in semi-arid and arid areas need only a small amount of extra moisture to respond significantly with higher yields. The provision for overflow around the tips of the bunds is recommended, though occurrence of overflow is usually rare. A larger C:CA ratio can be designed but it should not exceed 5:1.

3.2.7 Semi-circular earth bunds for annual crops

Semi-circular bunds (also known as 'demi-lunes' or crescent-shaped bunds) for field crops, are a variation of the system described fro trees, but made wider to accommodate field crop. They are commonly found in West Africa, where they are used for production of millet, sorghum and other food grains, in areas receiving as little as 200-300m.

Design features

The semi-circular bunds for annual crops are generally small, each with a radius of about 2 metres. Because of their small size, the total number of bunds can be about 300 per hectare, the size of the cultivated area enclosed by the bunds depends on the amount of rainfall but since they are used in low rainfall areas, the average catchment: cultivated area ratio is normally about 4:1. Runoff water is collected from the area above the bund and ponded in the basin created by the bund (Figure 3.7). 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.

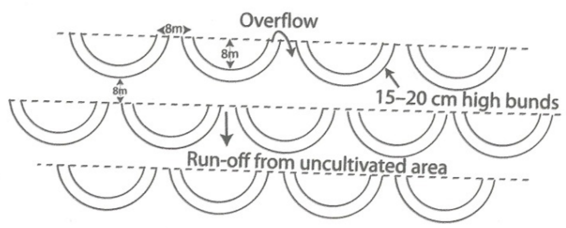


Figure 3.7(a) Layout of a semi-circular bunds for annual crops	**b) Semi-circular bund with sorghum** *(photo courtesy of J.N. Poda)*

3.2.8 Negarims

Negarims are a microcatchment method of designing basins, comprising diamond-shaped basins surrounded by small earth bunds with an infiltration pit in the lowest corner of each. The entire square is enclosed by an earth bund to avoid overtopping. This technique is appropriate for small-scale tree planting in low rainfall areas. Negarim microcatchments are appropriate for establishing orchards, especially *fruit trees such as papaya, mangoes and citrus. They are also* used to establish trees planted as woodlots, fodder trees/shrubs in rangelands or other trees around homesteads. If the catchment is well maintained, 30-80 % of the rain can be harvested and used by the crop using negarims microcatchments.

Design features

The negarim's "diamond shape" is basically a regular square made of earthen bunds, in which the "V" shape faces upslope forming the lowest corner of the square. At this corner, an infiltration basin is made and at the centre of the basin, a pit is dug where a tree crop is planted. Runoff is collected from within the basin and stored in the infiltration pit for use by the tree crop. The field plan therefore comprises a series of such squares, creating microcatchments and utilizing the land very efficiently (Figure 3.8).

Basic parameters

Catchment size (m^2)	3 - 250
Cropping area (m^2)	1 - 10
Catchment: Cropping Ratio	3:1 - 25:1
Precipitation	150 - 600 mm/a
Slope	1 - 20%

The *negarim* is best when laid on even ground. The usual dimensions are 5-10 m in width and 10-25 m in length with bunds which are about 15-20 cm high at the apex and the basins can be 40 cm deep. The top of the bund should be at least 25 cm wide and side slopes should be at least in the range of 1:1 in order to reduce soil erosion during rainstorms. Whenever possible, the bunds should be provided with a grass cover as protection against erosion. The size of infiltration pit also varies with basin size, but a depth of 40 cm should not be exceeded in order to avoid water losses through deep percolation and to reduce the workload for excavation. Excavated soil from the pit should be used for construction of the bunds.

Negarims are recommended for relatively flat to gentle slopes ranging about 1-5%. Where the ground slope exceeds 2.0%, the bund height near the infiltration pit must be increased. The catchment areas for negarims can range from 16 m^2 in slightly wetter areas to 1,000 m^2 in very dry zones.

Negarims require deep soils, about 2 m to allow storage of harvested runoff water. They can be applied in areas with as low as 150 mm annual rainfall, but are preferable in areas receiving 300-700 mm annual rainfall. It is normally recommended to construct a lcut-off drain above the area treated with negarims so as to avoid excessive external flows from destroying the bunds.

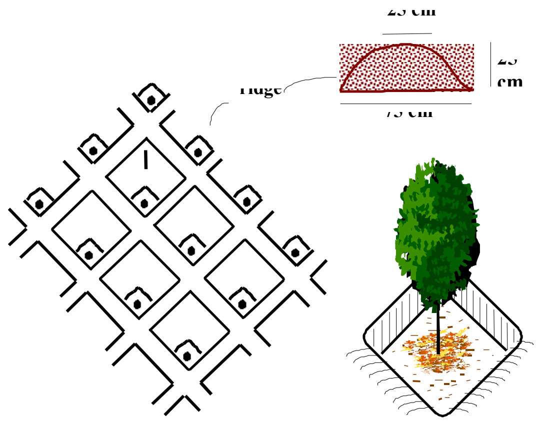


Figure 3.8(a) Negarim microcatchments for trees | **(b) Negarims with bushes** *(photo courtesy of Thieb Oweis)*

<u>**Advantages of Negarims**</u>

Negarims offer optimum water harvesting conditions since the entire area is enclosed. They also conserve the soil while retaining more moisture at the crop root zone. Negarim microcatchments are neat and precise, and relatively easy to construct. They have very little conveyance losses as water is used close to the source. The structures are also cost-effective to construct, utilizing mostly manual labour. Negarims are efficient in land utilization. Negarims have been observed to improve fruit tree establishment by 60% while also increasing the yields of trees in very low rainfall areas, which receive 300 mm per annum.

<u>**Limitations of Negarims**</u>

Negarims are not easily mechanised, therefore they are limited to small scale farming. Also, the diamond shape makes cultivation between tree lines rather cumbersome. Negarim microcatchments have relatively low returns on investment particularly on labour. Yet it is not a cheap technique to implement. Generally, one person-day is required to build (on average) two units, and costs per unit rise considerably as the microcatchment size increases. In the case of multipurpose trees in arid/semi-arid areas, a major benefit could be just the soil conservation effect or fodder since trees sometimes take long before they can be considered productive.

<u>**Maintenance**</u>

As with all water harvesting structures, negarims require regular maintenance to repair damages to bunds, which may occur if storms are heavy soon after construction when the bunds are not yet fully consolidated. The site should be inspected after each significant rainfall as breakages can have a "domino" effect on the entire field if left unrepaired. Regular desilting of the basins and using the spoil to rebuild the bunds is also recommended.

Manure or compost should be applied to the planting pit to improve soil fertility and water-holding capacity. If grasses and herbs are allowed to develop in the catchment area, the runoff will be reduced and thus it is necessary to weed the negarims, but maintain compaction in the catchment side of the structure. Sometimes the negarims is allowed to grow grass which is used as fodder, thus providing some return on the construction investment. Regular weeding is necessary in the vicinity of the planting pit.

3.2.9 V-Basins

These are excavated basins, having a "V" shape, and with a capacity of about 2.5 m^3. They are constructed with 10 m ridges extending upslope, but the tips lie on the contour. There is no precise spacing between individual microcatchments, but in practice, the catchment area can be up to 150 m^2 in the driest areas. In certain more favourable zones, an alternative design is used for individual catchments of 5 m by 5 m and pits of 1.2 m^3 capacity. Tree seedlings are planted in the pit at the base of the "V" immediately after the beginning of the rains (Figure 3.9).

V-shaped earthen bunds with a length (the distance between the tips of each bund) of about 10-100 m and a height of 1-2 m. Often, they are aligned in long, staggered rows facing up the slope. The space along the contour between adjacent bunds is usually about half the length of the bund. The tips of the bund should be protected against erosion, as water often overflows round them. Large bunds are usually constructed by machinery and only rarely by hand. They are used to support trees, shrubs, and annual crops such as sorghum and pearl millet.

	
Figure 3.9 (a) Sketch of a V-shaped basin	**(b) A V-shaped basin with tree seedling** *(photo courtesy of Francis Koome)*

3.2.10 Broad-bed and furrow

Broad-bed and furrow systems are a modification of contour ridges, with a deliberate effort to ensure that there is a "catchment" ahead of the furrow. It is a within-field microcatchment water harvesting system.

Design features

Broad-bed and furrow systems involves making wider, flat ridges about 1 - 2 m wide and shallow, wide furrows about 0.5 m wide and 0.2-0.2 m deep. These dimensions vary with slope gradient, the size of the microcatchment area necessary and the amount of rainfall available. The catchment area is left uncultivated and clear of vegetation to maximize runoff.

Crops can be planted on the sides of the furrow and on the ridges. Plants that need much water, such as beans and peas, are usually planted on the upper side of the furrow, and cereal crops, such as maize and millet, are usually planted on the ridges (Figure 3.10).

The system is suitable where the annual rainfall is from 350 -700 mm, land is of gentle slope (about 0.5-3.0% steepness) and soil should have good infiltration properties. Although the furrows increase crop yields in the drier areas, they have high labour demands and certain intricacies are involved in making them, which can be a constraint.

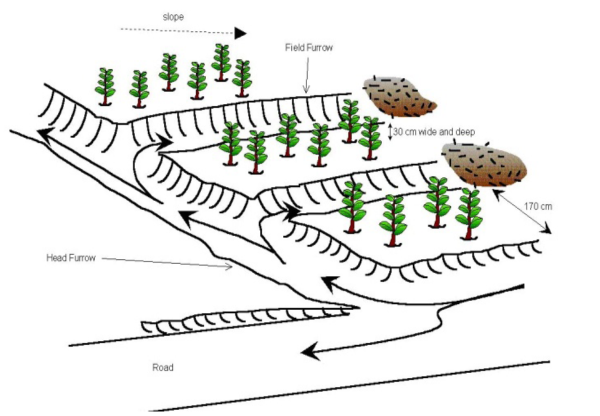


Figure 3.10 (a) Sketch of a Broad bed and furrow microcatchment System

(b) **Broad-bed and furrow system** (Photo courtesy of H. Mahoo)

3.3 Stone Bunding

Where stones are available, they can be used to construct bunds which facilitate water harvesting, for both microcatchment and macro-catchment systems. Normally a line of stones (stone bund) is laid along a contour at intervals commensurate with the crop being grown and the catchment areas to generate the requisite runoff.

Advantages of stone bunding

Stone bunding is simple to implement at the local level. It facilitates soil moisture conservation for crop production and reduces soil erosion. Stone bunds do not readily wash away and, therefore, the technique is not vulnerable to unusual and variable intensity rainfall events. The structure tends to be stronger and long lasting.

Limitations

The main limitation is shortages of stones in many areas. Also, carrying and arranging the stones can be quite labour intensive.

Maintenance of stone bunds

A certain level of maintenance is needed since during heavy runoff events, stone bunds may be overtopped or some stones may be dislodged. These should be replaced by plugging any gaps with small stones where runoff forms a tunnel. As the sediments build up ahead of the structure, eventually stone bunds silt-up and their water harvesting efficiency declines. It normally takes three seasons or more for this to happen, and occurs more rapidly where bunds are wider apart, and on steeper slopes. Bunds should be built up progressively increasing the height packed stones, to reduce siltation, while maintaining the effect of slowing runoff.

Types of stone bunds

There are many ways to arrange stones across a slope and achieve stone bunding for runoff farming, soil and water conservation, gully control, stabilization of embankments and generally, for water control. However, two types of stone bunding can be distinguished for runoff farming using overland flow; (i) contour stone bunds, and (ii) permeable rock dams. These are briefly described bellow:

3.3.1. Contour stone bunds

Contour stone bunds are buffer strips created by arranging stones in across the slope on the contour to form a barrier. However, the crop is grown just ahead of the stone bund, leaving the upper end of the terrace free to make a catchment (Figure 3.11). Contour stone bunds do not concentrate runoff but keep it spread. They also reduce the rate of runoff allowing infiltration, and any excess water passes through the bund but at low non-erosive velocities.

Design features

In this system, stones are packed across the slope on the contour to form a barrier. However, the crop is grown just ahead of the stone bund, leaving the upper end of the terrace free to make a catchment.

Stone bunding should result in structures at least 25 cm high with a base width of 35 to 40 cm. They are set in a trench of 5 to 10 cm depth which increases stability. The spacing between bunds varies but is usually between 15 to 30 m.

Stone bunds are especially safer to use since they form a porous barrier, which slows down runoff, and is unlikely to fail in case of extreme flooding. Stone bunding is particularly suited to semi-arid lands, where stones are available and is commonly practiced in areas receiving 200-750 mm of annual rainfall.

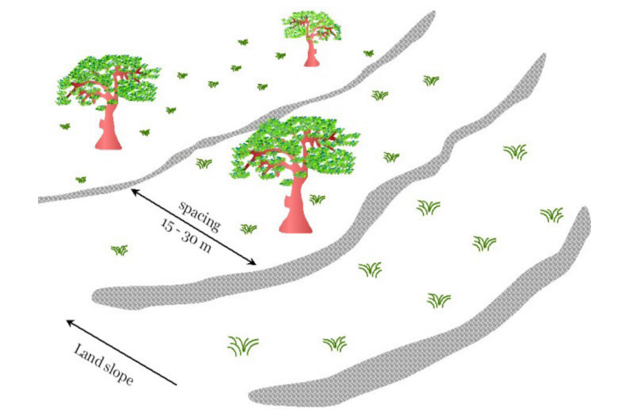


Figure 3.11(a) Contour stone bunds for overland flow	(b) Contour sone bunds *(photo courtesy of J.N. Poda)*

3.3.2 Semi-circular bunds made with stones

Where stones are available, semi-circular bunds can be constructed by packing the stones in a semi-circle, and excavating a ponding area within the run-on area. Stone-bunded semi-circular hoops can be used either for annual crops or for trees. Various sizes are allowable, including larger structures in which the radius of the semi-circle can be up to 20 metres. The bund height can be up to 0.5 m high at the middle with side slopes of 3:1 (horizontal: vertical). Due to the larger dimensions of the bunds, the distance between the tips of two adjacent structures in one row is 10 m while 30 metres are possible between the base of the upper structure and the tips of the lower one. These types of bunds last longer and can absorb unexpectedly high runoff flows, because the excess runoff filters through the bund walls without causing erosion damage. For this reason, they can be used on steeper slopes, including rehabilitation of hillsides and mountain areas (Figure 3.12).

	
Figure 3.12(a) Semi-circular bunds made with stones *(photo by Donald Gabriels)*	**(b) Stone stabilized semi-circular bunds** *(photo courtesy of Benoit Sarr)*

Advantages of semi-circular bunds

Semi-circular bunds are more efficient in terms of impounded area to bund volume than other equivalent structures -such as trapezoidal bunds for example.

Major limitations

The main limitations associated with semi-circular bunds includes the fact that construction cannot easily be mechanized. They are difficult to construct with animal draft. They also require regular maintenance.

Maintenance

Semi-circular earthen bunds require more regular maintenance than those made of stone, as the bunds are easily flattened by the effects of rainfall. The most critical period for semi-circular bunds is when rainstorms occur just after construction, since at this time the bunds are not yet fully consolidated. Any breakages must be repaired immediately. If damage occurs, it is recommended that a diversion ditch is provided if not already constructed. Semi-circular bunds which are used for trees normally need repairs of initial breaches only. This is because in the course of time, a dense network of the perennial grasses will protect the bunds against erosion and damage. But if animals have access into the bunded area and are allowed to graze, then regular maintenance of the bund is necessary. In the case of annual crops, semi-circular bunds have to be repaired before planting each season, and organic manure added wherever possible.

3.3.3 Permeable rock Check dams

Permeable rock dams are long, low structures consisting of well packed stones, creating contour bunds across valley floors. The design allows runoff which normally concentrates in the centre of the valley or gully, to be spread across the whole valley floor, thus making conditions more favourable for plant growth. The pond excess runoff ahead of the stone bund to increase water conservation, while also reducing runoff and erosion damage. Gradually the dam silts up with fertile deposits. Usually a series of dams is built along the same valley floor, giving stability to the valley system as a whole. Permeable rock dams are popular in semi arid areas especially for rehabilitation of denuded rangelands.

Design features

Permeable rock dams are usually made across wide, shallow valley beds. The structures are constructed of stones rising to about 0.5 to 1 m in height and can be up to 50 m wide and 300 m in length. The larger and longer the dams the more costly the operation so it is beneficial to estimate the required size previous to construction. Permeable rock dams can be used for crop production in arid to semi-arid areas having 200 -750 mm annual rainfall. They can be made on all agricultural soils, and are particularly beneficial to poor soils which improve due to soil conservation (Figure 3.13). The method is recommended for gentle slopes: not exceeding 2% so as to achieve effective water spreading.

The design of catchment: cultivated area ratio is not necessary as the catchment area and the extent of the cultivated land are predetermined. However, the catchment characteristics influence the size of structure and whether a spillway is required or not. It is therefore recommended to design the system size as a whole based on the expected rainfall characteristics of the area. This ensures that the check dams are of appropriate size and can cope with the larger flows than expected.

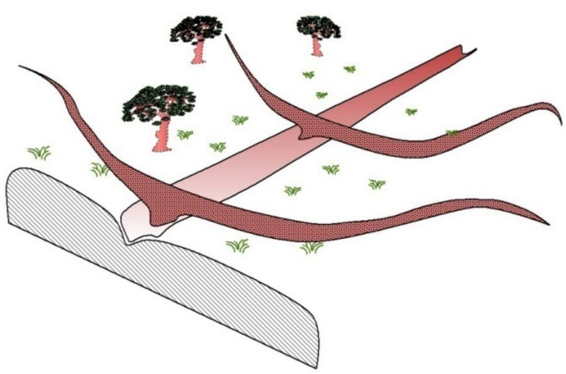


Figure 3.13 (a). Permeable rock dam for harvesting channel flow	(b) Permeable rock dam with crops for runoff harvesting *(photo by Bancy Mati)*

The size of catchment area determines the height of the stone bund at the centre of the valley. This height can be reduced if there are a number of check dams in series down the slope. In this case, starting from the highest dam the lower dam should come to the height of the base of the previous dam. It is often beneficial to locate a dam where there are naturally occurring deeper section of the valley so as not to risk huge areas of flooding behind the dam and the creation of large shallow pools. Where back flooding does take place it is often necessary to build embankments or dykes to protect farmlands, homesteads and other infrastructure.

Advantages

Unlike conventional dams, the porous nature of permeable rock dams enables excess overland flows to be safely dissipated without damage or undermining the structure. Also, sediments are deposited ahead of the structure thus enabling conservation of both water and soil. The temporary ponding of runoff by the permeable rock dams helps recharge soil moisture and thus, certain crops, fodder grass and trees can be grown ahead and behind the check dam with better results.

Precautions

The main limitation of permeable rock dams is that they are particularly site-specific, and require large quantities of loose stones. Their transport and labour to pack them properly into bunds is costly. Thus, they can be expensive and are mostly done as community projects.

3.4 Pitting Systems

Pitting, or the digging of holes of various sizes for growing crops, is one of the easiest methods of water harvesting and conservation for both microcatchment and external catchment systems. The method involves growing field crops in holes of various sizes (Figure 3.14). Planting pits increases crop yields by a combination of moisture conservation and harvesting of runoff from the spaces between the pits. In addition, soil fertility is restored since the manure and fertilizer cannot be lost through surface runoff. Planting pits are recommended for relatively low rainfall areas, or where moisture conservation is desired, to enable a crop survive drought and increase production.

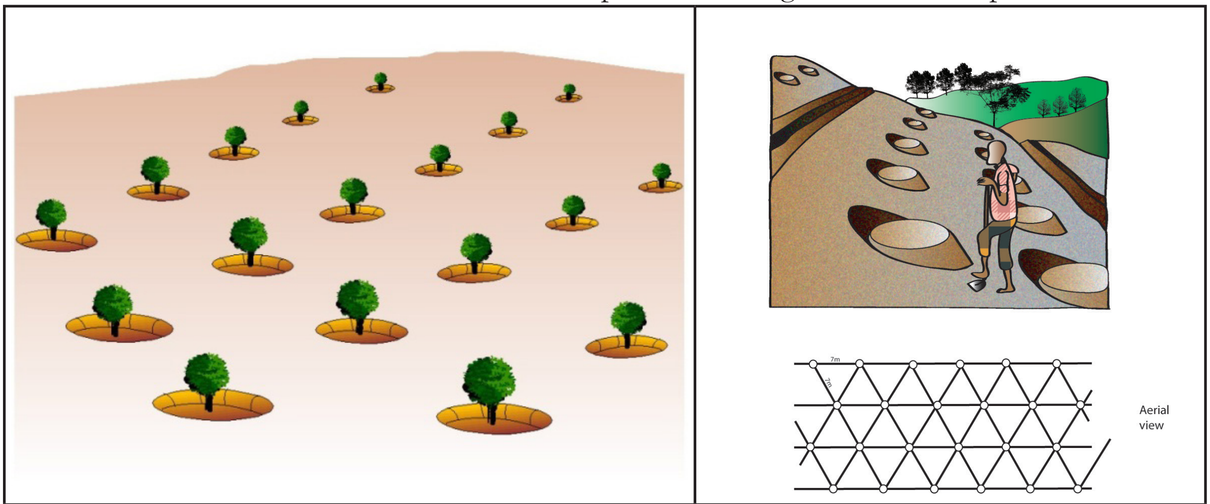


Figure 3.14(a) Sketch of planting pits micro-catchment system	(b) Arrangement of pitting on a hillside

Traditionally, pitting was normally done for tree crops such as bananas, coffee, tea, fruit trees and certain vegetables. However, pitting for field crops such as maize, millet and beans is nouvelle to many African agronomic cultures, and the technology has to be encouraged.

Precautions

In pitting systems, it is important that the microcatchment can yield runoff properly. Thus, once the crop is growing in the planting pit, the open spaces between the pits should be kept clear of weeds. To maintain a compacted microcatchment, the land between the pits is not tilled, but weeds can be cleared manually without disturbing the soil or by use of herbicides. It is usually recommended to construct a storm-water diversion ditch above the cropped area to protect pits from being overrun by excessively high flood flows. The number of seeds to be planted per pit should be commensurate with requirements for crop spacing.

Advantages of planting pits

Planting pits absorb runoff water, enabling the crop to survive drought and increase yields. Planting pits can make a difference between getting a harvest or nothing at all in a low rainfall season. Once prepared, planting pits can be re-used for about two to four crop seasons with good results. Since water is concentrated in the pit, runoff and soil erosion on other parts of the farm is reduced while weeds are reduced. By concentrating manure and fertilizers in the pit, soil fertility is enhanced improving crop performance while avoiding wastage of nutrient resources.

Limitations

The main limitation with planting pits is the heavy labour demanded in preparing the pits the first time. Also, they may not work well in water logging soils. There is also the danger of overtopping collapse if unexpectedly high storm intensities occur. Since some of the land is taken over as the microcatchment, the total plant population in a field may be less than with conventional cultivation, thereby lowering gross yields. However, the benefits using planting pits far outweigh the limitations.

<u>Types of planting pits</u>

For microcatchment water harvesting systems, various types of pits can be distinguished, usually developed locally and having local names. Examples include the *zai, "tumbukiza, chololo pit, five-by-nine pits, matengo pits* and various types of infiltration pits and ditches. These are described here as follows:

3.4.1 Zai Pits

The "zai" or zay (sometimes called *tassa*) pitting system is adopted from the Sahel Region of West Africa where it has been traditionally practiced. They utilize shallow, wide pits used to concentrate surface runoff and grow cereal crops in semi-arid zones. Manure is usually added into the pit to improve fertility. Zai pits work through a combination of water harvesting and conservation of both moisture and soil fertility in the pit.

<u>Design features</u>

The zai system consists of small individual basins spaced about 1 m apart and large enough to catch all the rainfall that falls. The pits are shallow and wide, measuring about 30-60 cm diameter and 15-30 cm deep. During construction, holes are dug about 60 cm diameter and 30 cm deep. The topsoil is separated from the subsoil.

The topsoil is mixed with well composted manure and returned to the pit, ensuring that a certain depth of hole is left to act as ponding zone. The subsoil is used to create a small bund on the downhill side of the pit.

Crop seeds are then planted, about 4-12 seeds of maize, sorghum, millet other crops (Figure 3.15). The number of seeds per zai pit depends on crop type, variety, climate and expected run-on. The main problem with zai pits includes the high labour demands for digging the pits.

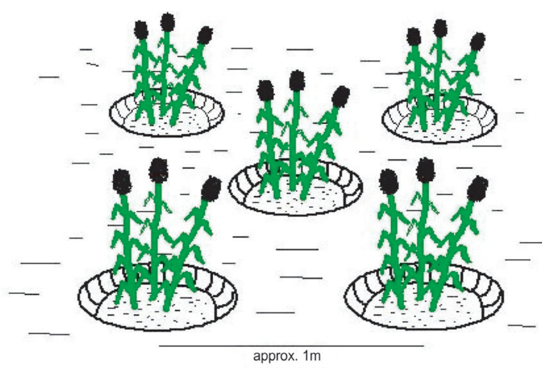


Figure 3.15(a) Zai microcatchment System for cereal Crops

(b) Zai microcatchment system with millet *(photo courtesy of Poda, J.N.)*

3.4.2 Five-by-Nine pits

Five-by-nine pits are planting pits for enhancing water harvesting and storage for field crops such as maize. They are slightly larger than Zai pits and square in shape. The name "five by nine" is based on the five or nine maize seeds planted at the pit across the pit diagonals (five for dry areas and nine for wet areas). The system is popular for low rainfall areas of central and eastern Kenya.

Technical details

In design, five-by-nine pits are 60 cm square and 60 cm deep. Thus they are larger than Zai pits but have a square shape (Figure 3.16). One or two maize seeds are planted across the diagonals of the pit creating a seed rate of either five plants or nine in the pit. Because the pit is larger, it can hold more manure and is capable of achieving higher yield that have a long-lasting effect. The pit can be re-used for periods up to 2 years.

Advantages

Just like with Zai pits, the five –by-nine pits hold more runoff and conserve soil fertility, increasing production even when rains are less than normal.

Limitations

Huge labour demand digging the pits since they are larger than Zai. Also, the danger of planting the crop in the subsoil if the top soil is not handled well.

Figure 3.16 (a) Five by nine pits for maize *(photos by Bancy Mati)* **(b) Square pits with nwly planted sugar-cane**

3.4.3 Tumbukiza Pits

Tumbukiza pits are relatively larger pits used for fodder and fruit tree production, especially bananas. *Tumbukiza* in the Swahili language means, "throw all in." *Tumbukiza* pits have been popular in Kenya for smallholder dairy development on small plots of land and also for commercial banana production. Tumbukiza system is used in both microcatchment and external catchment systems

Design features

Tumbukiza involves digging huge pits, which are least 0.6-0.9 m square or in diameter and with similar dimensions in depth. The pits are then filled with crop residues, any available vegetative material and farmyard manure and topsoil. A space is left within the pit to create a ponding zone for water, while the subsoil is used to create a small earthen bund around the pit. A fodder or banana crop is planted in the pit (Figure 3.17). The general arrangement should allow runoff from surrounding areas to get into the pit and increase water storage.

Due to the large volume of the *tumbukiza* pit, the fodder therefore grows rapidly, making it possible to have at least a fodder harvest per pit per month. Moreover, the *tumbukiza* pit stores moisture much longer, enabling napier grass to survive in drier environments and fodder production during the dry season. However, the high labour demands in excavating *tumbukiza* pits forms a major limitation of the system.

Figure 3.17 (a) Newly excavated tumbukiza pit planted with Napier grass *(Photo by B. Mati)*

(b) Tumbukiza pits with banana crop *(photo by Faith M. Livingstone)*

3.4.4 Chololo Pits

Chololo pits are small planting pits used for water harvesting and conservation, but which accommodate just one or two seeds of an annual crop. They are so named after the village in Dodoma Region of Tanzania where they were invented. They are like the spot tillage practised under conservation agriculture, but differ in that the rest of the field is fully cultivated.

Main design features

In design, Chololo pits comprise a series of pits about 22 cm in diameter and 30 cm in depth. The pits are spaced 60 cm apart within rows, and 90 cm between rows, with the rows running along the contour. The soil removed during excavation is used to make a small bund around the hole. Inside the pit, 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. Normally, one or a few seeds of either maize, millet or sorghum are planted per hole.

3.4.5 Water-Retaining Pits

Water-retaining pits trap runoff and allow it to seep into the soil. A series of pits are dug into the ground where runoff normally occurs. The soil from the pits is used to make banks around the pits (keep the topsoil and put it on top of the banks). Furrows carry excess water from one pit to the next. The size of the pits depends on the amount of runoff: a typical size is 2 m square and 1 m deep. The pits are enriched with manure and can be used for growing vegetables (Figure 3.18) or other field crops.

Figure 3.18 Water retaining pits for vegetable production *(Source: FAO Mediatek)*

4. EXTERNAL CATCHMENT WATER HARVESTING SYSTEMS

4.1 What is an External Catchment System?

An external catchment system (or macro-catchment system), sometimes known as water spreading systems involves diverting excess overland flows from its natural course and conveying it to nearby areas where it is used for supplemental irrigation of crops, trees or fodder. The harvested water is stored solely in the crop root zone. Normally, the cropped area should have deep soils which have good soil moisture retention properties. Typical catchment areas include hills, rocky surfaces, home compounds and open fields.

External catchment systems are common in semi-desert and arid zones where the land topography is relatively flat to gently sloping. Sometimes, flush floods could be the only source of water used in these systems. The crops grown should be tolerant to temporary water-logging, as well as being drought resistant. External catchment systems are commonly used in the Horn of Africa countries, particularly for fodder establishment and supplementary irrigation of drought resistant crops.

Salient features

External catchment systems handle large runoff flows diverted from beyond the cropped area, and thus are essentially macro-catchment systems. This means that the run-on area is designed to accommodate relatively larger flows (Figure 4.1). The runoff is diverted from open fields, rocky surfaces, gullies and ephemeral streams, homesteads, roads and other surfaces onto cropland. Techniques include diverting and spreading floods (spate irrigation), collecting water in basins and channeling it through canals. Macro-catchments with large storage structures can be used for large-scale and community-based projects.

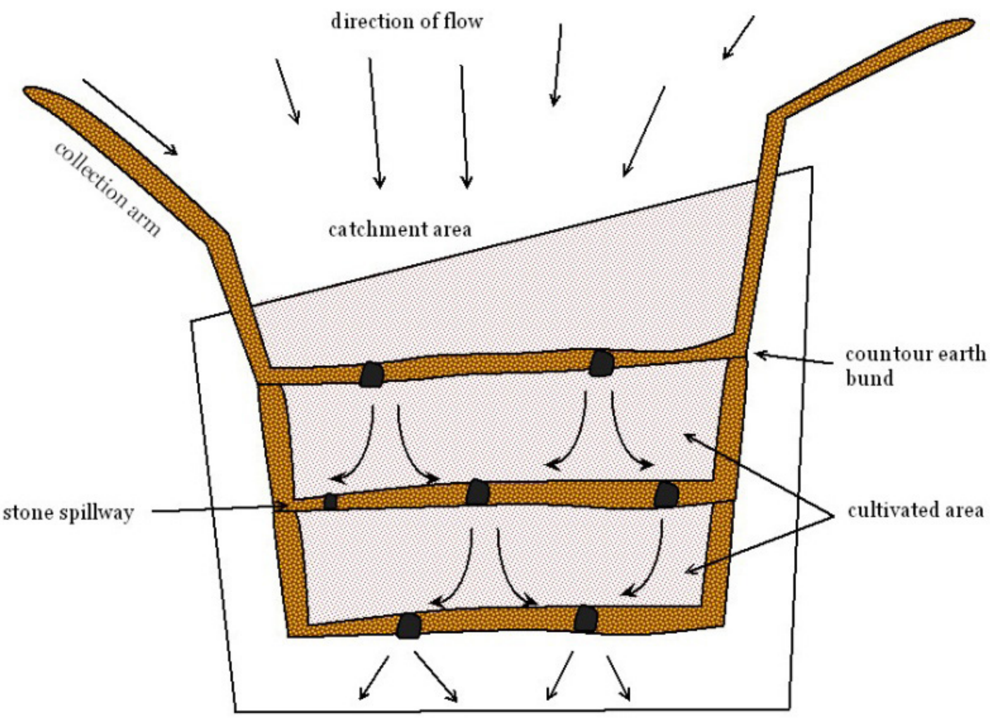


Figure 4.1. Sketch of an external catchment runoff farming system

Design characteristics of external catchment systems:

- Overland flow or hill flow can be harvested

- runoff is stored in soil profile
- catchment area is usually 30 - 200 metres in length
- Ratio of catchment: cultivated area usually 2:1 to 10:1 (large)
- Must have provision for overflow of excess water
- May result in uneven plant growth unless land levelled.

Advantages

External catchment systems are able to harvest and store more water, therefore, can make use of small rainfall events more efficiently that microcatchment systems. They utilize excess runoff which would otherwise cause erosion damage, thus protecting the environment from degradation.

Limitations

Due to the large volumes of flow handled, external catchment systems have higher failure rates and thus require proper engineering design features. They are usually more costly due to the need for land levelling, larger bunding structures and specialised expertise needed for them to work. They are suited to special conditions in terms of land topography, source of runoff, soil profile characteristics, and hence may not be applicable to a wide range of users.

Types of external catchment systems

External catchment systems are designed in various shapes and sizes, and some of the most common types being trapezoidal bunds, excavated bunded basins, T-basin.

4.2 Trapezoidal Bunds

Trapezoidal bunds are large bunded structures, forming trapezoidal basins which utilize external catchment or runoff from beyond the immediate cropped area. The cropped area can enclose up to 1 ha of land and thus impound large amounts of runoff. Crops are planted in the basin area enclosed by soil bunds. This technique is suitable for area with 250-500mm of annual rainfall.

Design features

Trapezoidal basins are made facing the direction of runoff. The base width can be up to 100 m long along the contour with the wing walls turned about 135 degrees facing upslope. The maximum bund height is 0.6m decreasing to 0.2m at the tips. The bunds are usually spaced about 20 m apart, and overflow arrangements are made to ensure excess runoff from one bund can find its way to the next. Excess runoff is discharged around the tips of the bunds. Field crops such as sorghum and millet are grown in the basins.

Trapezoidal bunds are recommended for an even topography on slopes ranging 0.25-1.5% and on non-cracking soils which have high moisture retention properties, e.g. clays. Trapezoidal bunds have an indigenous origin and are used by farmers in arid and semi-arid environments in the Horn of Africa (Kenya, Somalia and Sudan). An example is the "teras" system, which comprises a widespread system of large earth bunds with straight walls, used to cultivate drought-tolerant crops, e.g., sorghum, in areas with a low annual rainfall of 150-300 mm. Due to their large size, mechanized construction is usually preferred.

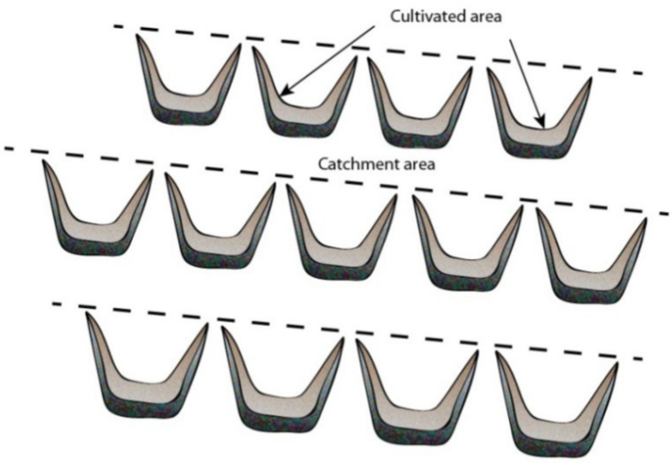


Figure 4.2 Layout of Trapezoidal bunds for crops

Precautions

The main concern with trapezoidal bunds is whether they are socio-economically viable depending on labour costs, and equipment used to construct them. The technique can be used for trees and grass but is best suited for row crops where manual work is the mode of cultivation. The standard design method is used to size the required catchment area.

4.3 Excavated Bunded Basins (Majaluba)

Excavated bunded basins (or *majaluba in Swahili)* are small basins that usually utilize an external catchment. This system is one of the methods of runoff utilization, management and storage for the production of paddy rice and is widely used in the semi-arid areas of Mwanza, Shinyanga, Tabora, Singida and Dodoma regions of Tanzania.

Design features

Majaluba are constructed by digging to a depth of 0.2 m to 0.5 m, and by using the scooped soil to build a bund around the field perimeter. Normally, the bunds have a height of between 0.3 m to 0.7 m above the ground (Figure 4.3). Farmers usually start with small-sized basins, for example, 10 m by 10 m, and then go into large areas of about 1 ha, as they assess the safety and efficacy of the basin. Majaluba are practiced in areas where rainfall ranges about 400 to 800 mm per year. Generally, the potential evapotranspiration exceeds rainfall most of the time and the rainfall regime is highly variable in quantity, timing and distribution, hence the need for its storage. The soils for Majaluba system are generally shallow, but with high moisture holding capacity.

	
Figure 4.3 (a) Excavated bunded basins (Majaluba) *(photos by Bancy Mati)*	**(b) Excavated bunded basin with rice crop under water harvesting**

4.4 Root Zone Basins

Root zone basins are essentially external catchment systems utilizing surface runoff from e.g. paths, roads and compounds. However, they make use of slightly raised bumps, which are about 0.05 m high across the path, into collecting channels, and from there, water is directed into the basins. Root zone basins are circular pits, but deeper than Zai or other normal pits. In design, root zone basins measure about 0.6 m to 1.2 m diameter and 0.1 m to 0.3 m in bund-height (Figure 4.4). Root zone basins essentially utilize an external catchment. The depth of tillage within the basin is usually increased up to 0.6 cm with a view to improve root zone storage capacity for the harvested water. Moisture retention in the root zone is enhanced through addition of manure, mulching and using vegetative materials. Thus, with small rainfall events, root zone basins are more effective than Zai pits.

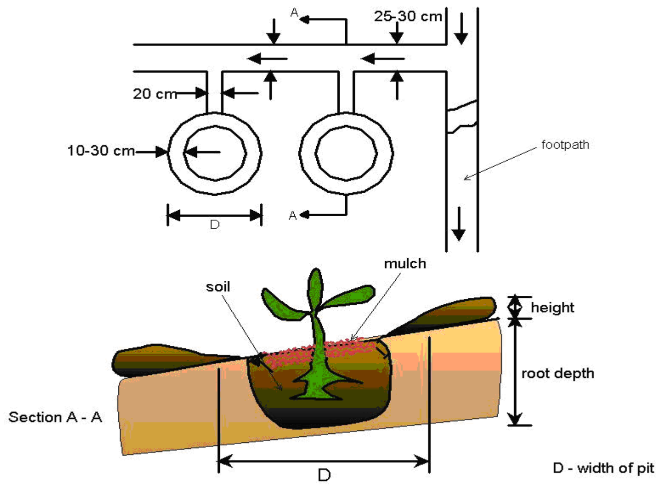


Figure 4.4 Sketch of a root zone basin showing top view and side Profile

(b) Root zone basins planted with bananas *(photo by Bancy Mati)*

4.5 T-basins

T-basins comprise a series of interconnected square or semi-circular basins (looking like an inverted T), connected to external catchments such as footpaths and roads through a system of narrow channels. The water generated from the catchments is conveyed to the basins via the channels. The water collected in this manner is held in the T-basins, from where it infiltrates into the root zone of the surrounding crops (Figure 4.5). As opposed to the circular root zone basins, this system can be used for both tree and non-tree crops. Traditionally, the system is used by farmers in western Kenya for growing bananas, mangoes, citrus and passion fruit.

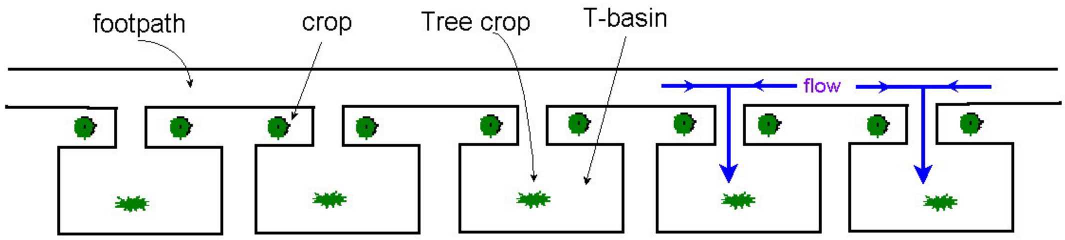


Figure 4.5 Arrangement of T-basins in a field

4.6 External Catchment With Zingg Terrace

Surface runoff can be harvested from external catchments for use in cultivated fields on a slope steeper than is recommended for most runoff farming systems. This is made possible by constructing a back-slope graded terrace variously known as reverse-sloping bench or Zingg terrace. In this design, the upper part of the terrace bed also serves as a catchment to provide runoff onto inner part of the same terrace on which crops are grown (Figure 4.6). The system is recommended for gentle slope (< 6%) with deep soils, where the catchment to cropped area ratios range about 1:1 to 2:1. Zingg terraces are especially useful when combined with runoff harvesting from small roads and footpaths to grow cereals and legumes, such as maize, beans, cow peas.

Figure 4.6 Zingg terrace with external catchment system *(Photo by Bancy Mati)*

4.7 Retention Ditches

Retention ditches are open channels dug along the contour to catch and retain incoming runoff and hold it until it seeps into the ground. They are an alternative to cutoff drains when there is no nearby waterway to discharge the runoff into. The source of runoff can be open fields, home compounds or roads. Retention dirches are essentailly external catchment systems but since they do not have overflow arrangements, the expected runoff volumes should be manageable. Tree crops such as bananas are grown within the channel (Figure 4.7). They are often used for water conservation in semi-arid areas.

	
Figure 4.7(a) Newly excavated retention ditch *(photos by Bancy Mati)*	**(b) Retention ditch with banana crop**

4.8 Infiltration Ditches

Infiltration ditches are a variation of diversion ditches, but whose purpose is to catch excess runoff, hold it in the ditch and enhance lateral seepage to cropped land adjacent to the ditch. They utilize an external catchment such as a roads, open fields or other sources of runoff. They consist of a ditch, 0.7-1.5 m deep, and about 1.0- 2.0 m wide, dug along the contour, upslope from a crop field. Water is diverted from the roadside into the ditch, which is blocked at the other end (Figure 4.8). Water trapped in the ditch seeps into the soil. The crop is usually downslope of the ditch and benefits from lateral seepage thus increasing production.

Figure 4.8 Infiltration ditch adjacent to cropped maize field *(photo by Bancy Mati)*

4.9 Lock-and-Spill Ditch System

A lock-and-spill ditch is a relatively deep channel excavated across the slope, but whose furrow has low cross-walls that divide the ditch into separate basins (locks) to encourage infiltration. It utilizes an external catchment, including roads, where runoff flows are manageable, and thus is closed at the ends to form a ditch. A lock-and-spill ditch works by ensuring that excessive flows are temporarily retained in the small basins (lock) created by the cross walls. Excess runoff overtops these cross-walls and spills towards the next basin increasing water retention time and thus enhancing infiltration. The ditches catch water and soil and therefore get silted up. Regular de-silting is thus necessary. The cropped area is outside the ditch in adjacent land down slope. The crop benefits by lateral seepages of the water. Lock-and-spill ditches are popular in dry and semi-arid areas.

	
Figure 4.9 Newly excavated Lock-and-spill ditch *(photo by Bancy Mati)*	**(b) Lock-and-spill ditches on a hillside** *(photo courtesy of Donald Gabriels)*

4.10 Graded Lock and Spill Drain

A lock and-spill drain differs from the ditch system in that the channel has a small slope to allow drainage of excess water. However, the channel is graded to allow drainage (Figure 4.10). Low cross-walls divide the drain bed into separate basins (locks) to encourage infiltration. During heavy rains, the runoff overtops these cross-walls and spills toward the discharge outlet. The graded earth bunds are stabilised with vegetation and their outlets reinforced with stones. The drains catch water and soil allowing the crop to benefit through lateral seepage. Regular desilting is necessary to ensure the drain is functional every season.

	
Figure 4.10(a) Newly excavated graded lock-and-spill drain *(photo courtesy of Janvier Gassasira)*	**(b) Graded lock-and-spill drain on a hill-side** *(photo courtesy of Donald Gabriels)*

5. FLOODWATER HARVESTING SYSTEMS

5.1 What is Floodwater Harvesting?

Floodwater harvesting, also called 'Large catchment water harvesting' or 'spate irrigation' or 'floodwater farming' are essentially external catchment rainwater harvesting systems which utilize relatively large runoff volumes usually in the form of stream flow (channel flow). It comprises systems with catchments being many square kilometres in size, from which runoff water flows through the bed of an ephemeral stream, river or watercourse. Thus, these systems generally require special diversion structures such as canals, embankments, spillways, gates and other infrastructure normally associated with surface irrigation. Since the stream-flows tend to be turbulent, special handling is necessary to prevent flood damage to the structures.

Main Characteristics of flood water farming

The distinguishing feature from simple external catchment systems is the fact that under floodwater farming, runoff flows comprise turbulent channel flow harvested either (a) by spreading within channel bed/valley floor or (b) by diversion structures, but in both cases, the runoff is stored in soil profile. The diversion of flood flow is achieved by raising the water level through temporary, semi-permanent or concrete weirs, bunds and accompanying diversion channels and water control infrastructure. Generally, the catchment areas are long (may be several kilometres), necessitating more complex structures of dams and distribution networks. The ratio catchment: cultivated area is usually larger than above 10:1 Due to large volumes of flow, there must be provision for overflow of excess water from the cropped area. In almost all the cases, flood water harvesting is used in spate irrigation systems, either on-site or off-site.

Floodwater farming is suited to arid and semi arid areas where the nature of rainfall tends to result in flush floods or excessive flows in valleys, gullies, ephemeral streams and other types of channels. The diversion of this floodwater into cultivated fields is therefore an important component of making use of lands which are too dry for conventional rain fed farming.

Advantages

Floodwater harvesting renders dry valleys and flood plains more productive. A variety of crops are grown in systems of floodwater harvesting. In the wadis, trees are grown sometimes intercropped with cereals. By taping the excess runoff, flooding downstream is reduced, while soil and water conservation is improved.

Types of floodwater harvesting systems

Typology of floodwater harvesting may be by source of runoff. In this case, there are systems which utilize flush floods from valleys and natural watercourses. They include:

a) Stream-bed systems (wadi cultivation)
b) Ephemeral stream diversion
c) Water spreading bunds
d) Road runoff harvesting with ditch system
e) Road runoff harvesting with basins
f) Cultivated reservoirs

g) Hillside conduit systems

h) Inundation farming (recession flood water farming)

The common methods of Floodwater Harvesting Systems are briefly described below.

5.2 Floodwater Harvesting Within Stream-Bed

Floodwater harvesting within stream-bed (stream-bed water harvesting or "wadi" cultivation), involves the cultivation of dry riverbeds using floodwater within the bed of the watercourse. The system utilizes barriers such as permeable rock dams or earth banks to intercept water flowing in an ephemeral stream and spread it across the valley with terraces to enhance infiltration. During the rainy season, water flow is dammed and as a result, inundates the valley bottom of the flood plain. The water is forced to infiltrate and the wetted area can be used for agriculture or pasture improvement.

Design features

The most important feature is to have a spillway with sufficient capacity to allow for the excess peak flows that may pass through the ephemeral stream. Stream cross-walls should not exceed 1 m, and should be made preferably using stones or reinforced with gabions. The top of the wall should be all at the same level, so as to create uniform land behind it, allow excess water to overflow along its entire length. Distances between walls along the stream bed are determined according to the slope of the *stream* bed and the height of the wall.

The cultivated areas are mainly used for growing cereals, such as wheat sorghum and millet, planted immediately after the water has subsided (figure 5.1). Valley-bottom flood water harvesting systems must be equipped with water control structures e.g. overflow spillways and gates, to protect the cropped land from excessive flooding. In areas where late rains occur in for example the maturing stage, these would damage rather than improve production. Simple reservoirs would not be feasible under such conditions.

Stream-bed water harvesting is common in wide ephemeral streams *(wadi)* beds with gentle slopes. As a result of the slow water velocity, eroded sediments usually settle in the stream-bed and create good agricultural land. This may occur naturally or can be achieved by the construction of earthen or stone check dams to reduce the flow speed and allow soil sediments to settle.

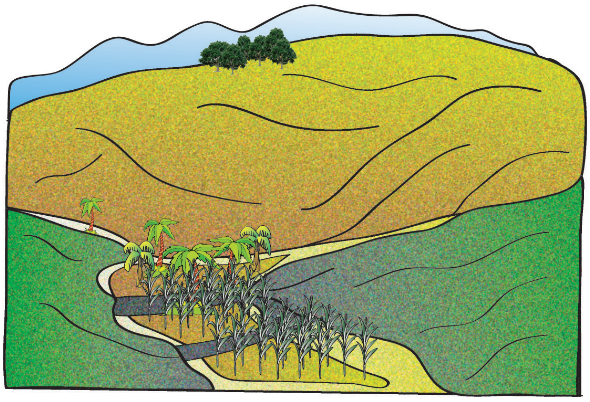


Figure 5.1 (a) Sketch of water harvesting within stream-bed	**(b) Stream-bed water harvesting with crops** *(photo by Bancy Mati)*

Advantages

The benefits of flood water harvesting within stream-bed to the environment are substantial. The system optimizes water use efficiency, by increasing infiltration while reducing wastage of water and evaporation losses. Soil erosion and general land degradation are reduced. The productive capacity of the land is enhanced.

Limitations

The main problems associated with this type of water harvesting are the costs and the maintenance of the walls. Another problem could be other developments upstream such that little water reaches the *stream* beds, with the result that downstream crops become increasingly water-stressed. In such circumstances, an integrated watershed development approach is needed to decide on a fair allocation of the water supply.

5.3 Ephemeral Stream Diversion

Ephemeral stream diversion (or floodwater diversion) are techniques where water is forced to leave its natural course and conveyed to nearby cropping areas. This involves diversion of flood flow from highlands into lowlands or levelled basins in the arid lowlands (Figure 5.2). The field is divided into closed basins and water is distributed either through a channel or in a basin-to-basin cascade using small spillways. In these systems, the catchment areas are many square kilometres in size – require more complex structures of dams and distribution networks and a higher technical input than the other two water harvesting methods.

Design features

Ephemeral stream diversion utilizes earthen embankments that divert part of the flow from their natural watercourse or ephemeral stream into artificially made channels. The water is led to bunded cultivated lands where it is impounded for infiltration. Structures such as earth bunds, stone walls or brushwood barriers are used to control the flow.

Ephemeral stream diversion can be used in very low rainfall areas, receiving 100-550 mm annual rainfall. The embankments conveying the storm-water can range from small to extremely large (5 m to 10 m high). It is necessary to do land levelling and demarcation of cultivated plots and then construct river diversions and flood protection works. The cultivated area should have deep soils with good water retention properties.

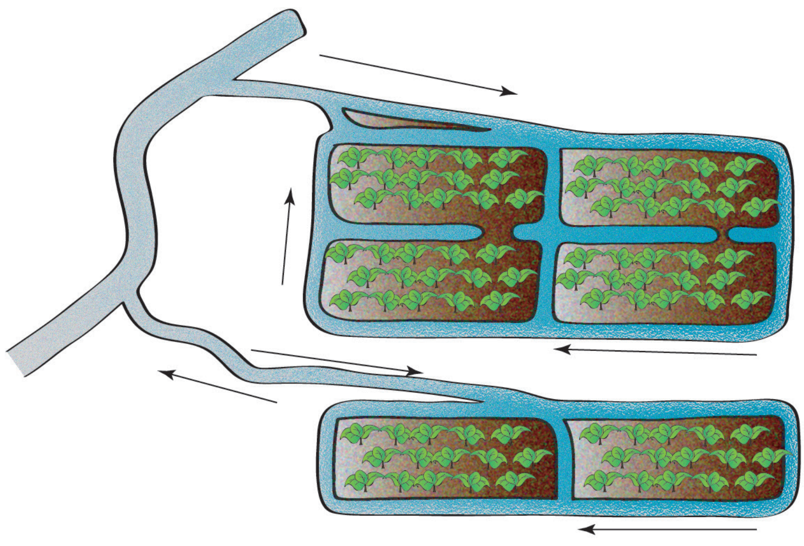


Figure 5.2 Floodwater diversion from ephemeral stream

Advantages

Ephemeral stream diversion helps convert dry valleys and flood plains into more productive lands, growing a variety of crops such as fruit trees, forage crops and cereals The maintenance of the embankments is very labour intensive, hence it is carried out on a community scale. Floodwater diversion can be low cost where only manual labour is needed.

Limitations

Ephemeral stream diversion usually handles very turbulent flows, thus the physical infrastructure construction and land levelling costs can be high. These structures are subject to frequent damage and are likely to be washed away by large floods. Attempts to improve such systems by building permanent diversion structures such as concrete or stone-filled gabions often encounter problems with flows bypassing the structure or flood damage during heavy rains. Maintenance and labour can also be high, since the system requires de-silting and regular repair of channels and embankments due to frequent bund breakages. The different characteristics of each site make engineering design particularly site specific.

5.4 Water Spreading Bunds

Water spreading bunds (or "caag" system) is a method of flood water diversion, often applied in situations where trapezoidal bunds are not suitable. They are suitable to areas where runoff discharges are high and would damage trapezoidal bunds or where the crops to be grown are susceptible to the temporary water-logging, which is a characteristic of trapezoidal bunds. The major characteristic of water spreading bunds is that, as their name implies, are intended to spread water and not to impound it. They are usually used to spread floodwater which has either been diverted from a watercourse or has naturally spilled onto the floodplain (Figure 5.3). Water fills the top basin and spills around the end of the bund into the next basin. The bunds, which are usually made of earth, slow down the flow of floodwater and spread it over the land to be cultivated, thus allowing it to infiltrate.

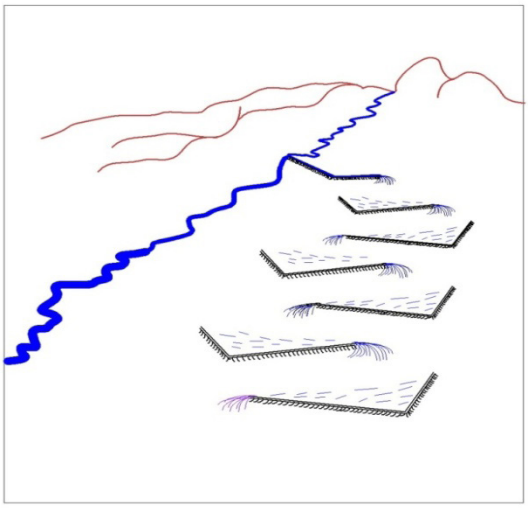


Figure 5.3 (a) Water spreading bunds	**(b) Water spreading bunds with tree crops** *(photo by B. Mati)*

Design features

Water spreading bunds can be used in arid and very arid areas where rainfall ranges 100 - 350 mm per annum They are suited to alluvial soils or floodplains with deep fertile soils, and land topography should be even and very gently sloping, less that 1% gradient. The technique of floodwater farming using water spreading bunds is very site-specific. The land must be sited close to the watercourse, usually on a floodplain with alluvial soils and low slopes. Generally, the bunds can be made measuring 60 cm high, 4.1 metres base width, and a top width of 50 cm. This gives stable side slopes of 3:1. A maximum bund length of 100 metres is normally recommended. Field crops such as millet, sorghum and pulses are grown in the ponded area.

5.5 Road Runoff Harvesting With Ditch System

Roads, footpaths, animal tracks, railway lines and other infrastructure are paved areas or made of compacted soil, often with surface crusts that produce high volume of runoff. These surfaces can be used as source of runoff in external catchment systems. However, the volumes of runoff can be quite high and tend to be concentrated into channels, falling in the category of "flood water harvesting". Harvesting surface runoff from roads, footpaths, railway lines and animal tracks has great potential for replicability. Road runoff harvesting systems vary from simple diversion structures directing surface water into crop fields, to deep trenches with check-dams in order to enable both flood and spate irrigation which are usually combined with bunded basins. A ditch system can be adopted for tree crops.

Design features

Road runoff harvesting with ditch system comprises an excavated main channel of about 50 - 300 m in length, which diverts road runoff from the road to the farm. Once in the farm, the runoff is led first into a channel made across the predominant slope, popularly known as "fanya chini" (rather like a diversion ditch). The channel dimensions are about 1.0 m deep and 1.0 to 2.0 m wide, and with earthen embankments which are 1.5 m high and spaced at 18 m apart, making them somewhat larger than the average size. The vertical intervals between structures are thus about 0.9 m. The embankments are stabilized with grass or other cover crop. At the end of this channel, the water is diverted around a bend into a similar channel, this time, and the flow being in the opposite direction. This system is repeated throughout the farm resulting in a zig-zag reticulated flow (figure 5.4). At certain points, water control gates can be constructed so as to direct the flow in the desired direction.

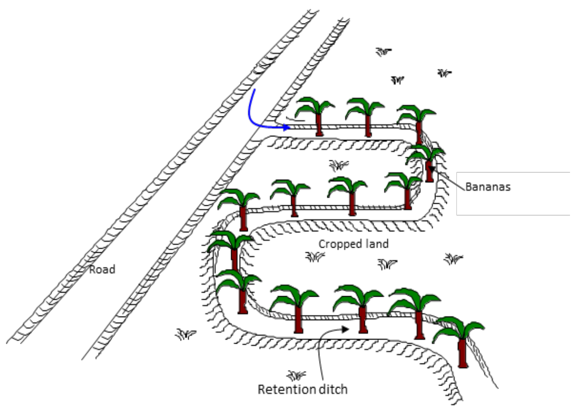


Figure 5.4 Road runoff harvesting with ditch system

(b) Bananas in ditch using road runoff harvesting *(photo by Bancy Mati)*

5.6 Road Runoff Harvesting with Retention Basins

Road runoff can also be channelled into retention basins and used to grow crops such as rice, wheat or maize. The main difference is that retention basins are used to grow field crops. Due to the large volumes of water expected, this method is recommended for areas with deep soils which are stable and unlikely to collapse when ponded.

Design features

In this system, the basins are usually rectangular, and can measure upwards of about 5 m long by 5 m wide. Each basin is enclosed by small earth bunds of about 25 cm height. The retaining bunds normally have a spillway on the lower side to allow excess flow into the next basin in a cascade pattern. The last basin should allow excess flow onto a stable surface such as a grassed area. The system functions by diverting and directing road runoff using shallow channels into the basins (Figure 5.5). The channel dimensions are variable, however, the most common are in the range of 1-1.5m deep, 1-2m wide, while length is dependent on farm size. Spacing of the channels/canals is arbitrary; however, 2-18m is common. It is recommended that terrace vertical spacing be used, however, that depends on ground slope. It is sometimes necessary to incorporate drop structures of about 5cm in height spaced at about 5 m intervals, in the channels to reduce the danger of bed erosion. Planting pits as for bananas should be located in the channel to encourage ponding in the pit and allow flow to the next without overtopping.

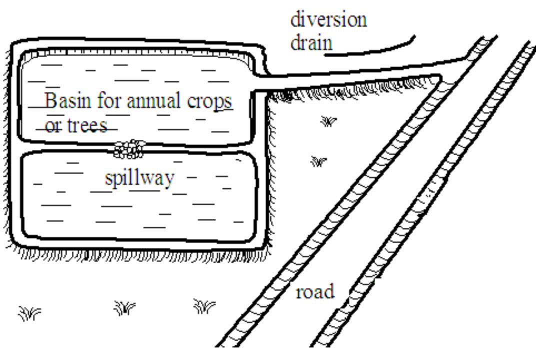


Figure 5.5(a) Road runoff harvesting with basins


(b) Road runoff harvesting onto Mmaize field *(photo by Bancy Mati)*

Advantages

Integrating RWH with road (and railway) drainage helps reduce erosion caused by water drained from the roads, railways and footpaths. It offers a readily available source of runoff for supplemental irrigation of crops. The road surface is normally paved or compacted hence there is no need for further treatment of the catchment for it to produce runoff in large quantities.

Limitations of road runoff harvesting

For road runoff harvesting with basins, there is usually the danger of water logging depending on type of crop in the basin. Where channels are dug deep into the infertile subsoil, fruit tree pits need a lot of manure to be mixed with top soil. There is also the danger of overtopping since road runoff can be turbulent. The system requires regular maintenance.

5.7 Cultivated Reservoirs

In this system, the flood water is harvested and diverted into cultivated basins where it is held and stored in the soil profile. The cultivated reservoirs are constructed by digging the field to a depth of about 0.2 m and the scooped soil is used to build a bund around the field perimeter. The bunding can be in the form of trapezoidal basins, rectangular basins bunded on three sides, e.g. teras used in Sudan, or the rectangular basins bunded on all four sides e.g. the "majaluba" systems of Tanzania. The main difference is large volumes of flood water used. Thus, cultivated reservoirs are larger and hold more water, therefore, they require the design and safety features used in other floodwater harvesting systems (Figure 5.6).

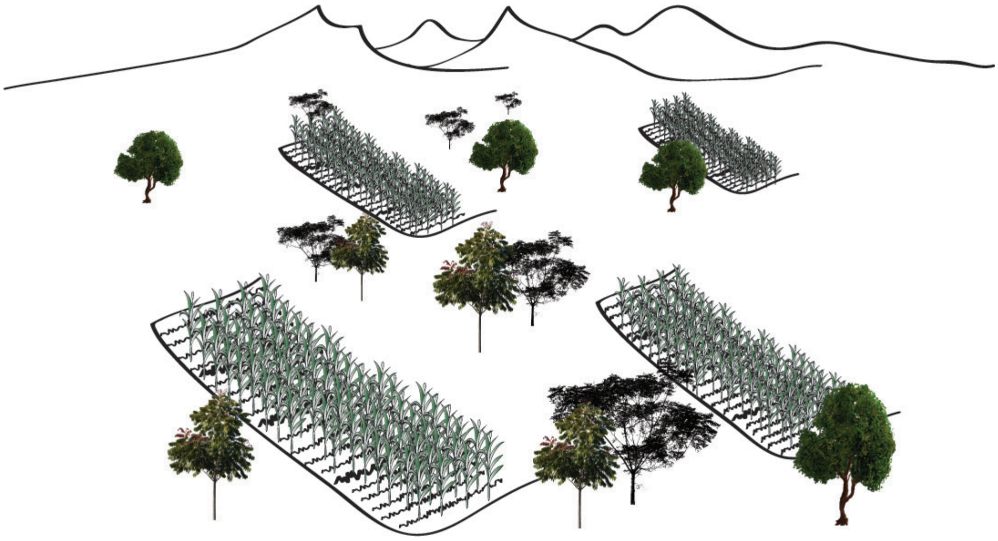


Figure 5.6 Layout of cultivated reservoirs

5.8 Hillside-Conduit Systems

Where runoff flows are collected from hilly areas far from the cultivated lands, a hillside conduit system can be constructed. This is an open channel, usually lined with stones or concrete to take the water quickly down to the farms without causing damage. The main characteristic is the manner of transferring the water, normally from small catchments uphill to cultivated reservoirs (Figure 5.7). The conduits are necessary for taking the water from the catchment down to the cultivated reservoirs with minimum loss by evaporation and seepage. Most external catchment and floodwater harvesting systems require such conduits.

Design features

Hillside conduit systems require proper design, preferably with the assistance of an engineer. They are also labour intensive. The system utilizes specially designed canals which carry runoff water from the hillside onto the fields downhill. The fields are levelled and surrounded by earthen or stone embankments with a spillway to drain the excess water to the next field downhill, foot of the slope. The whole arrangement is a cascade of fields such that when all fields in a series are filled, water is allowed to rejoin the watercourse or valley. Several feeder canals are used so as to make the distribution more efficient. The conduits should have sufficient slope to prevent sedimentation, otherwise they have to be cleared after heavy rainstorms. This technique can be applied to almost any crop.

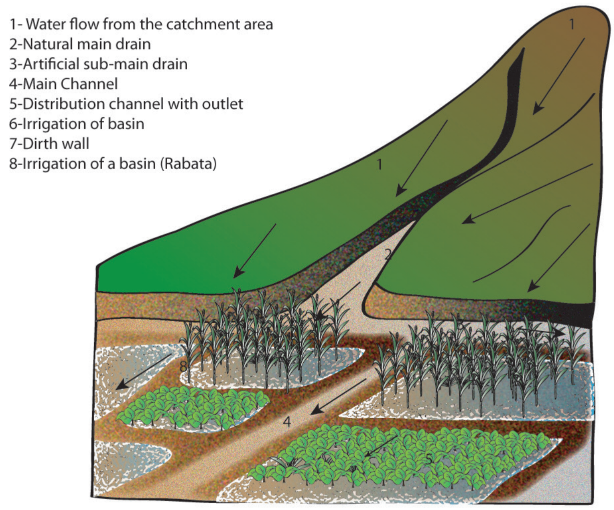


Figure 5.7 (a) Layout of a hillside conduit system for water harvesting

(b) Hillside conduit system delivering runoff to a farm *(photo by Bancy Mati)*

Advantages

Due to the high runoff producing characteristics of hillsides and other steep areas, rainfall storms of as little as 8 mm can initiate surface runoff. In field trials using runoff-harvesting system with a catchment size of one hectare, 48 percent of showers greater than 10 mm have been found to produce sufficient runoff to cause inflow into bunded basins. Field crops such as sorghum and millet are grown in otherwise very arid conditions.

5.8 Inundation farming

Inundation (recession flood water farming) is the practice of collecting runoff behind a bund where it stands until the planting date for the crop approaches. It is a method of water spreading in the stream-bed and can also be described as a method of recession farming. It is applied in areas with broken topography. The technique is also applicable to naturally occurring short-term flooding in plains and valleys. It is an external catchment system where large flows are expected, that are stored in the valleys. The land is then drained, and the crop is sown and grows to maturity using the water stored in the soil.

Design features

Inundation farming involves construction of earthen bunds across the valley bottom to catch and store runoff and silt from the surrounding barren hills. The system may include a series of embankments with sluice gates and spillways to create several flood areas. A design catchment to cropped area ratio of at least 15:1 is usually used. The structure is provided with a spillway and sluice gates to help in controlling the amount of flooding. The size of these structures varies greatly, but some systems run for several kilometres with one structure spilling excess flow to the next downstream and so on. Normally, planting is done at the end of the wet season using stored soil moisture. The selection of suitable crop types and varieties, especially those which withstand water-logging is also important as the soils may be poorly airated early in the growing period.

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7. APPENDICES

Appendix 1. Estimated crop water requirements for tropical conditions

Crop	Days to maturity / harvest	rainfall (mm)	
Bulrush millet	70	250-450	
Finger millet	75	230-500	
Sorghum	75	200-500	(300-650)
Groundnuts	50	180-550	
Tepary beans	60	180-320	
Cow peas	60	190-400	
Green grams	75	190-400	
Beans	70	230-450	(250-500)
Dolichos	100	200- 700	
Pigeon peas	no	370-650	
"(bimodal)	180	500-800	
Soya beans	80	350-680	(450-825)
Sunflower	75	180-550	
Simsim	90	300-600	
Cassava	180	500-1000	
Cotton	170	550-950	(550-950)
Banana	365	900-1700	(700- I 700)
Mango		800- 1000	
Passion fruit		900-2000	
Pawpaw		1000-1500	
Citrus		800-1400	(650-950)
Coffee (Arabica)		900- 1500	(800-1200)
(Robusta)		1100-2000	
Macadamia		750- 1200	
Sugarcane		1250-1800	(1000-1500)
Tobacco	150	400- 700	(300-900)

Source: Adapted from Jaetzold and Schimidt (1983). Figures in brackets are from Deorenbos and Pruit (1977)

Appendix 2. Crop Tolerance to Drought and Water-logging

	Ideal water requirements	Drought tolerance	Tolerance to water-logging
Sorghum	High (450-600 mm per season)	Yes	Yes
Pearl millet	Less than sorghum	Very good	No
Maize	High (450-600 mm per season)	Yes	No
Grain legumes	As sorghum	Most	No
Fodder & grasses	Low to high	Yes	?
Trees	Variable	Variable	Some

Source: FAO 2002

Appendix 3: Choice of Groups for Runoff farming

Crop Group	Examples	Well suited type of WH (others might also be possible)
Trees	Pistacchio, almond, fruit trees, fodder trees, citrus trees, eucalyptus	• Microcatchments (bunds, terraces, semi-circular) • Macrocatchment (liman etc.) • Floodwater diversion
Cereals	Sorghum Millet Wheat	• Microcatchment (semi-circular) • Macrocatchments (trapezoidal bunds) • Floodwater diversion
Horticultural crops	Pulses (Water) melons	• Floodwater diversion
Rangeland grasses	Local grasses	• Microcatchments (semi-circular loops, bunds)

Source: FAO, 2002

Appendix 4: Preferred climatic zone and drought tolerance of trees:

Tree Species	Rainfall 150-500 mm/a	Rainfall 500-900 mm/a	Tolerance to temporary water-logging
Acacia albida	Yes	Yes	Yes
Acacia nilotica	Yes	Yes	Yes
Acacia saligna	Yes	No	Yes
Acacia Senegal	Yes	Yes	No
Acacia seyal	Yes	Yes	Yes
Acacia tortilis	Yes	Yes	No
Albizia lebbeck	No	Yes	No
Antalaea indica	No	Yes	Some
Balanites aegyptiaca	Yes	Yes	Yes
Cassia siamea	No	Yes	No
Casuarina equisetifolia	No	Yes	Some
Colophospermum mopane	Yes	Yes	Yes
Cordeauxia edulis	Yes	No	?
Cordia sinensis	Yes	No	?
Delonix elata	No	Yes	?
Eucalyptus camaldulensis	Yes	Yes	Yes
Prosopis chilensis	Yes	Yes	Some
Prosopis cineraria	Yes	Yes	Yes
Prosopis juliflora	Yes	Yes	Yes
Ziziphus mauritiana	Yes	Yes	Yes

Appendix 5: Earthwork/stonework for various water harvesting systems

System	Earthwork (m³/ha treated)						Stonework (m³/ha treated)	
Slope %	Negarim micro-catchments (trees)	Contour bunds (trees)	Semi circular bunds	Contour ridges (crops)	Trapezoidal bunds (crops)	Water spreading bunds (crops)	Contour stone bunds (crops)	Permeable rock dams (crops)
0.5	500	240	105	480	370	305	40	70
1.0	500	360	105	480	670	455	40	140
1.5	500	360	105	480	970	N/R*	40	208
2.0	500	360	210	480	N/R*	N/R*	55	280
5.0	835	360	210	480	N/R*	N/R*	55	N/R*

* Not recommended

Source: Citchley and Siegert, 1991

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