

Water Harvesting Techniques:  
Training and Construction Manual

Consultancy Sub-report

No. 2

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# 1. Introduction

## 1.1 The basis of water harvesting: History and perspectives

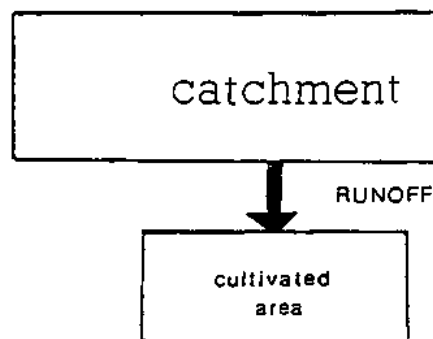
As land pressure rises, more and more marginal areas in the world are being used for agriculture. Much of this land is located in the arid or semi-arid belts where rain falls irregularly and much of the precious water is soon lost as surface runoff. Recent droughts have highlighted the risks to human beings and livestock, which occur when rains falter or fail.

While irrigation may be the most obvious response to drought, it has proved costly and can only benefit a fortunate few. There is now increasing interest in a low cost alternative - generally referred to as "water harvesting".

Water harvesting is the collection of runoff for productive purposes. Instead of runoff being left to cause erosion, it is harvested and utilized. In the semi-arid drought-prone areas where it is already practised, water harvesting is a directly productive form of soil and water conservation. Both yields and reliability of production can be significantly improved with this method.

Water harvesting (WH) can be considered as a rudimentary form of irrigation. The difference is that with WH the farmer (or more usually, the agro-pastoralist) has no control over timing. Runoff can only be harvested when it rains. In regions where crops are entirely rainfed, a reduction of 50% in the seasonal rainfall, for example, may result in a total crop failure. If, however, the available rain can be concentrated on a smaller area, reasonable yields will still be received. Of course in a year of severe drought there may be no runoff to collect, but an efficient water harvesting system will improve plant growth in the majority of years.

**Figure 1 The principle of water harvesting**



### 1.1.1 Historical perspectives

Various forms of water harvesting (WH) have been used traditionally throughout the centuries. Some of the very earliest agriculture, in the Middle East, was based on techniques such as diversion of "wadi" flow (spate flow from normally dry watercourses) onto agricultural fields. In the Negev Desert of Israel, WH systems dating back 4000 years or more have been discovered (Evanari *et al.* 1971). These schemes involved the clearing of hillsides from vegetation to increase runoff, which was then directed to fields on the plains.

Floodwater farming has been practised in the desert areas of Arizona and northwest New Mexico for at least the last 1000 years (Zaunderer and Hutchinson 1988). The Hopi Indians on the Colorado Plateau, cultivate fields situated at the mouth of ephemeral streams. Where the streams fan out, these fields are called "Akchin". Pacey and Cullis (1986) describe microcatchment techniques for tree growing, used in southern Tunisia, which were discovered in the nineteenth century by travelers. In the "Khadin" system of India, floodwater is impounded behind earth bunds, and crops then planted into the residual moisture when the water infiltrates.

The importance of traditional, small scale systems of WH in Sub-Saharan Africa is just beginning to be recognized (Critchley and Reij 1989). Simple stone lines are used, for example, in some West African countries, notably Burkina Faso, and earth bunding systems are found in Eastern Sudan and the Central Rangelands of Somalia.

### **1.1.2 Recent developments**

A growing awareness of the potential of water harvesting for improved crop production arose in the 1970s and 1980s, with the widespread droughts in Africa leaving a trail of crop failures. The stimulus was the well-documented work on WH in the Negev Desert of Israel (Evanari **et al.** 1971).

However much of the experience with WH gained in countries such as Israel, USA and Australia has limited relevance to resource-poor areas in the semi-arid regions of Africa and Asia. In Israel, research emphasis is on the hydrological aspects of microcatchments for fruit trees such as almonds and pistachio nuts. In the USA and Australia WH techniques are mainly applied for domestic and livestock water supply, and research is directed towards improving runoff yields from treated catchment surfaces.

A number of WH projects have been set up in Sub-Saharan Africa during the past decade. Their objectives have been to combat the effects of drought by improving plant production (usually annual food crops), and in certain areas rehabilitating abandoned and degraded land (Critchley and Reij 1989). However few of the projects have succeeded in combining technical efficiency with low cost and acceptability to the local farmers or agropastoralists. This is partially due to the lack of technical "know how" but also often due to the selection of an inappropriate approach with regard to the prevailing socio-economic conditions.

### **1.1.3 Future directions**

Appropriate systems should ideally evolve from the experience of traditional techniques - where these exist. They should also be based on lessons learned from the shortcomings of previous projects. Above all it is necessary that the systems are appreciated by the communities where they are introduced. Without popular participation and support, projects are unlikely to succeed.

Water harvesting technology is especially relevant to the semi-arid and arid areas where the problems of environmental degradation, drought and population pressures are most evident. It is an important component of the package of remedies for these problem zones, and there is no doubt that implementation of WH techniques will expand.

## **1.2 Definitions and classification**

Water harvesting in its broadest sense will be defined as the

**"collection of runoff for its productive use".**

Runoff may be harvested from roofs and ground surfaces as well as from intermittent or ephemeral watercourses.

Water harvesting techniques which harvest runoff from roofs or ground surfaces fall under the term:

### **RAINWATER HARVESTING**

while all systems which collect discharges from watercourses are grouped under the term:

### **FLOODWATER HARVESTING**

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 and duck ponds.

In the context of this manual, the end use is plant production, including fodder and trees.

Classification of water harvesting techniques is as varied as the terminology (Reij *et al.* 1988). Different authors use different names and often disagree about definitions.

It is not the intention of this manual to introduce new terms but instead it was considered appropriate to make use of the terminology which has been established within the context of the "Sub-Saharan Water Harvesting Study," undertaken by the World Bank in 1986-1989. The general and practical classification is presented in Figure 2.

## **1.3 Basic categories of water harvesting systems for plant production**

The water harvesting techniques described in this manual fall under three basic categories whose main characteristics are summarized as follows:

### **1.3.1 Microcatchments (rainwater harvesting)**

(sometimes referred to as "Within-Field Catchment System")

Main characteristics:

- overland flow harvested from short catchment length
- catchment length usually between 1 and 30 metres
- runoff stored in soil profile
- ratio catchment: cultivated area usually 1:1 to 3:1
- normally no provision for overflow
- plant growth is even

Typical Examples:

Negarim Microcatchments (for trees)

Contour Bunds (for trees)

Contour Ridges (for crops)

Semi-Circular Bunds (for range and fodder)

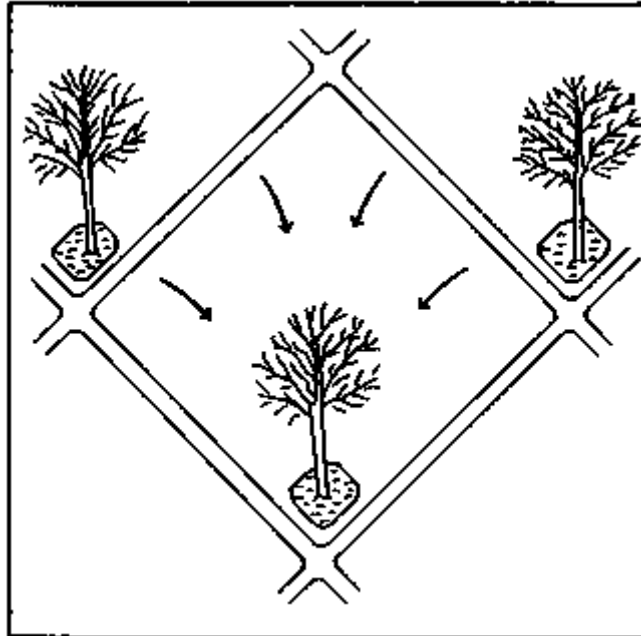
### **1.3.2 External catchment systems (rainwater harvesting)**

(Long Slope Catchment Technique)

Main Characteristics:

- overland flow or rill flow harvested
- runoff stored in soil profile
- catchment usually 30 - 200 metres in length
- ratio catchment: cultivated area usually 2:1 to 10:1
- provision for overflow of excess water
- uneven plant growth unless land levelled

**Figure 2 Microcatchment system: Negarim microcatchment for trees**

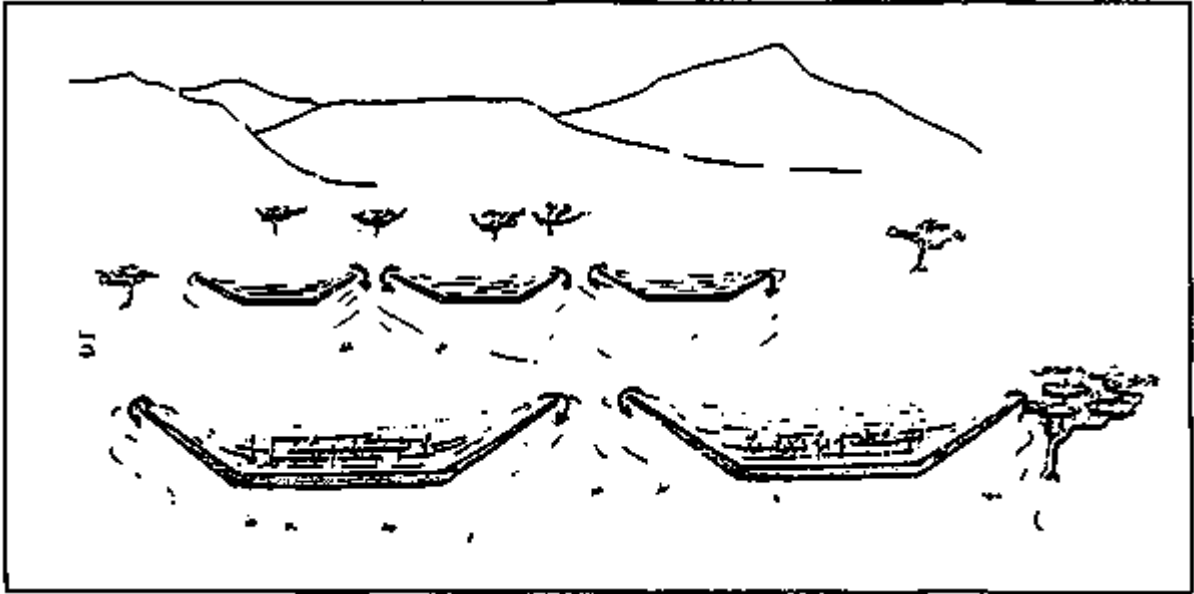


Typical Examples:

Trapezoidal Bunds (for crops)

Contour Stone Bunds (for crops)

**Figure 3 External catchment system: trapezoidal bunds for crops (Source: Critchley and Reij 1989)**



### 1.3.3 Floodwater farming (floodwater harvesting)

(often referred to as "Water Spreading" and sometimes "Spate Irrigation")

Main Characteristics:

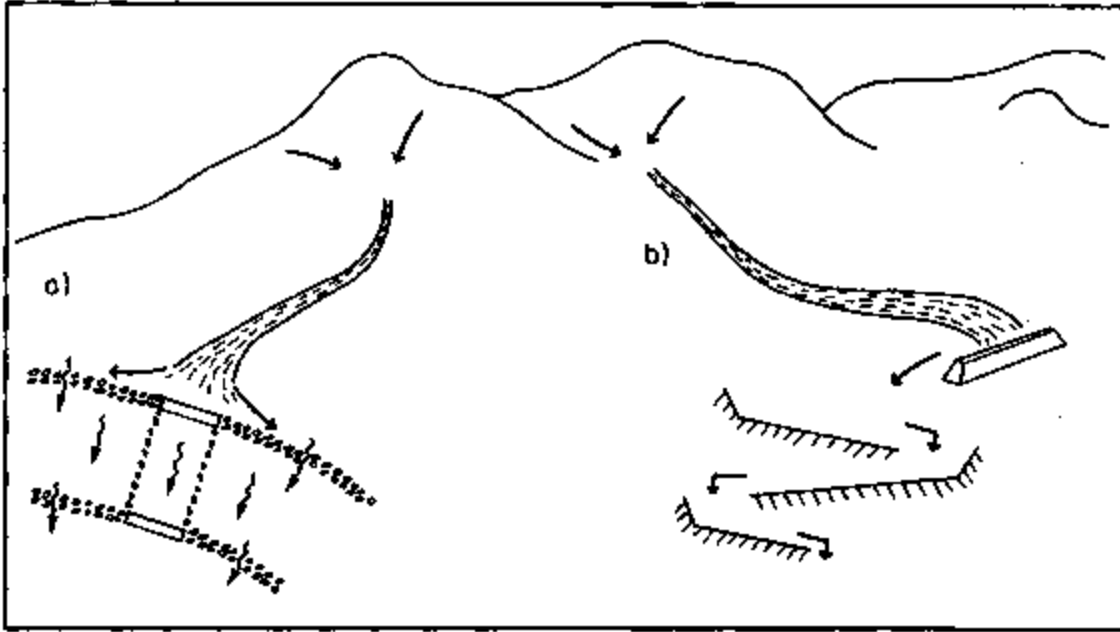
- turbulent channel flow harvested either (a) by diversion or (b) by spreading within channel bed/valley floor
- runoff stored in soil profile
- catchment long (may be several kilometres)
- ratio catchment: cultivated area above 10:1
- provision for overflow of excess water

Typical Examples:

Permeable Rock Dams (for crops)

Water Spreading Bunds (for crops)

**Figure 4 Floodwater farming systems: (a) spreading within channel bed; (b) diversion system**




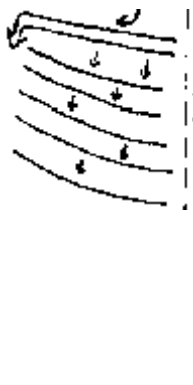
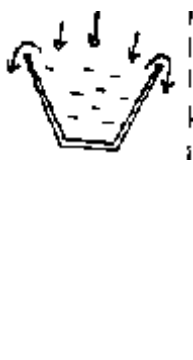
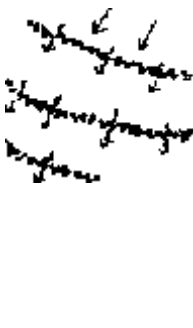
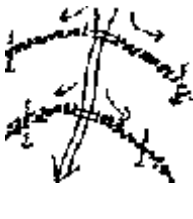
## 1.4 Overview of main WH systems


An overview of the main Water Harvesting systems which are described in detail in Section 5 is given in Table 1. This summary will be useful as a quick reference.

The eight techniques presented and explained in the manual are not the only water harvesting systems known but they do represent the major range of techniques for different situations and productive uses. In a number of cases, the system which is described here is the most typical example of a technique for which a number of variations exist - trapezoidal bunds are a case in point.

**Table 1 - Summary chart of main WH techniques**

	<b>Classification</b>	<b>Main Uses</b>	<b>Description</b>	<b>Where Appropriate</b>	<b>Limitations</b>	
negarim microcatchments	microcatchment (short slope catchment) technique	trees & grass	Closed grid of diamond shapes or open-ended "V" s formed by small earth ridges, with infiltration pits	For tree planting in situations where land is uneven or only a few trees are planted	Not easily mechanised therefore limited to small scale. Not easy to cultivate between tree lines	
contour bunds	Microcatchment (short slope catchment) technique	trees & grass	Earth bunds on contour spaced at 5-10 metres apart with furrows	For tree planting on a large scale especially when mechanised	Not suitable for uneven terrain	

	technique		upslope and cross-ties			
semi circular bunds	Micro catchment (short slope catchment) technique	rangeland & fodder (also trees)	Semi-circular shaped earth bunds with tips on contour. In a series with bunds in staggered formation	Useful for grass reseeding, fodder or tree planting in degraded rangeland	Cannot be mechanised therefore limited to areas with available hand labour	
contour ridges	microcatchment (short slope catchment) technique	crops	Small earth ridges on contour at 1.5m -5m apart with furrow upslope and cross-ties Uncultivated catchment between ridges	For crop production in semi-arid areas especially where soil fertile and easy to work	Requires new technique of land preparation and planting, therefore may be problem with acceptance	
trapezoidal bunds	External catchment (long slope catchment) technique	crops	Trapezoidal shaped earth bunds capturing runoff from external catchment and overflowing around wingtips	Widely suitable (in a variety of designs) for crop production in arid and semi-arid areas	Labour-intensive and uneven depth of runoff within plot.	
contour stone bunds	External catchment (long slope catchment) technique	crops	Small stone bunds constructed on the contour at spacing of 15-35 metres apart slowing and filtering runoff	Versatile system for crop production in a wide variety of situations. Easily constructed by resource-poor farmers	Only possible where abundant loose stone available	
permeable rock dams	Floodwater farming technique	crops	Long low rock dams across valleys slowing and spreading floodwater	Suitable for situation where gently sloping valleys are becoming gullies and	Very site-specific and needs considerable stone as well as provision of	

			as well as healing gullies	better water spreading is required	transport	
water spreading bunds	Floodwater farming technique	crops & rangeland	Earth bunds set at a gradient, with a "dogleg" shape, spreading diverted floodwater	For arid areas where water is diverted from watercourse onto crop or fodder block	Does not impound much water and maintenance high in early stages after construction	

## 2. Water and soil requirements

### 2.1 Water requirements of crops

#### 2.1.1 Introduction

For the design of water harvesting systems, it is necessary to assess the water requirement of the crop intended to be grown.

There have been various methods developed to determine the water requirement for specific plants. An excellent guide to the details of these calculations and different methods is the FAO Irrigation and Drainage Paper 24 "Crop Water Requirements". It should however be noted that formulae which give high accuracy also require a high accuracy of measured input data which in most places where water harvesting is practised will not be available.

#### 2.1.2 General estimates

In the absence of any measured climatic data, it is often adequate to use estimates of water requirements for common crops (Table 2). However, for a better understanding of the various factors and their interrelationship which influences the water demand of a specific plant, the following has been drawn from the FAO Irrigation Water Management Training Manual No. 3.

**Table 2 - APPROXIMATE VALUES OF SEASONAL CROP WATER NEEDS**

Crop	Crop water need (mm/total growing period)
Beans	300 – 500
Citrus	900 - 1200
Cotton	700 - 1300
Groundnut	500 - 700
Maize	500 - 800
Sorghum/millet	450 - 650

Soybean	450 - 700
Sunflower	600 - 1000

### 2.1.3 Factors influencing crop water requirements

#### i. Influence of climate

A certain crop grown in a sunny and hot climate needs more water per day than the same crop grown in a cloudy and cooler climate. There are, however, apart from sunshine and temperature, other climatic factors which influence the crop water need. These factors are humidity and wind speed. When it is dry, the crop water needs are higher than when it is humid. In windy climates, the crops will use more water than in calm climates.

The highest crop water needs are thus found in areas which are hot, dry, windy and sunny. The lowest values are found when it is cool, humid and cloudy with little or no wind.

From the above, it is clear that the crop grown in different climatic zones will have different water needs. For example, a certain maize variety grown in a cool climate will need less water per day than the same maize variety grown in a hotter climate.

It is therefore useful to take a certain standard crop or reference crop and determine how much water this crop needs per day in the various climatic regions. As a standard crop (or reference crop) grass has been chosen.

Table 4 indicates the average daily water needs of this reference grass crop. The daily water needs of the grass depend on the climatic zone (rainfall regime) and daily temperatures.

**Table 3 - EFFECT OF MAJOR CLIMATIC FACTORS ON CROP WATER NEEDS**

Climatic factor	Crop water need	
	High	Low
Sunshine	sunny (no clouds)	cloudy (no sun)
Temperature	hot	cool
Humidity	low (dry)	high (humid)
Wind speed	windy	little wind

**Table 4 - AVERAGE DAILY WATER NEED OF STANDARD GRASS DURING IRRIGATION SEASON (mm)**

Climatic zone	Mean daily temperature		
	low (< 15°C)	medium (15-25°C)	high (> 25°C)
Desert/arid	4-6	7-8	9-10

Semi-arid	4-5	6-7	8-9
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For the various field crops it is possible to determine how much water they need compared to the standard grass. A number of crops need less water than grass, a number of crops need more water than grass and other crops need more or less the same amount of water as grass. Understanding of this relationship is extremely important for the selection of crops to be grown in a water harvesting scheme (see Chapter 6, Crop Husbandry).

**Table 5 - CROP WATER NEEDS IN PEAK PERIOD OF VARIOUS CROPS COMPARED TO THE STANDARD GRASS CROP**

-30%	-10%	same as standard grass	+10%	+20%
Citrus Olives	Squash	Crucifers Groundnuts Melons Onions Peppers Grass Clean cultivated nuts & fruit trees	Barley Beans Maize Cotton Lentils Millet Safflower Sorghum Soybeans Sunflower Wheat	Nuts & fruit trees with cover crop

ii. Influence of crop type on crop water needs

The influence of the crop type on the crop water need is important in two ways.

- a. The crop type has an influence on the daily water needs of a fully grown crop; i.e. the peak daily water needs of a fully developed maize crop will need more water per day than a fully developed crop of onions.
- b. The crop type has an influence on the duration of the total growing season of the crop. There are short duration crops, e.g. peas, with a duration of the total growing season of 90-100 days and longer duration crops, e.g. melons, with a duration of the total growing season of 120-160 days. There are, of course, also perennial crops that are in the field for many years, such as fruit trees.

While, for example, the daily water need of melons may be less than the daily water need of beans, the seasonal water need of melons will be higher than that of beans because the duration of the total growing season of melons is much longer.

Data on the duration of the total growing season of the various crops grown in an area can best be obtained locally. These data may be obtained from, for example, the seed supplier, the Extension Service, the Irrigation Department or Ministry of Agriculture.

Table 6 gives some indicative values or approximate values for the duration of the total growing season for the various field crops. It should, however, be noted that the values are only rough approximations and it is much better to obtain the values locally.

**Table 6 - INDICATIVE VALUES OF THE TOTAL GROWING PERIOD**

Crop	Total growing period (days)	Crop	Total growing period (days)
Alfalfa	100-365	Melon	120-160
Barley/Oats/Wheat	120-150	Millet	105-140
Bean, green	75-90	Onion, green	70-95
dry	95-110	dry	150-210
Citrus	240-365	Pepper	120-210
Cotton	180-195	Rice	90-150
Grain/small	150-165	Sorghum	120-130
Lentil	150-170	Soybean	135-150
Maize, sweet	80-110	Squash	95-120
grain	125-180	Sunflower	125-130

From Table 6, it is obvious that there is a large variation of values not only between crops, but also within one crop type. In general, it can be assumed that the growing period for a certain crop is longer when the climate is cool and shorter when the climate is warm.

Crops differ in their response to moisture deficit. This characteristic is commonly termed "drought resistance" (Table 7 summarizes sensitivity to drought). When crop water requirements are not met, crops with a high drought sensitivity suffer greater reductions in yields than crops with a low sensitivity.

**Table 7 - GENERAL SENSITIVITY TO DROUGHT**

Group One:	(low sensitivity)	Groundnuts
	↓	Safflower
Group Two:	↓	Sorghum
	↓	Cotton
	↓	Sunflower
Group Three:	↓	Beans
Group Four:	(high sensitivity)	Maize

## 2.1.4 Calculation of crop water requirements

### i. Introduction

The calculation of crop water requirements by means of the two methods described in this section is relatively simple. The basic formula for the calculation reads as follows:

$$ET_{\text{crop}} = k_c \times E_{\text{to}}$$

where:

$ET_{\text{crop}}$  = the water requirement of a given crop in mm per unit of time e.g. mm/day, mm/month or mm/season.

$k_c$  = the "crop factor"

$E_{\text{to}}$  = the "reference crop evapotranspiration" in mm per unit of time e.g. mm/day, mm/month or mm/season.

## ii. $E_{\text{to}}$ - reference crop evapotranspiration

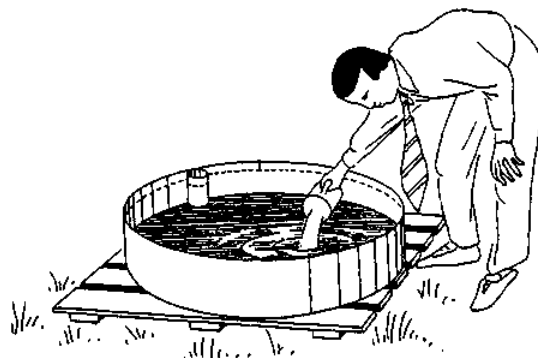
The reference crop evapotranspiration  $E_{\text{to}}$  (sometimes called potential evapotranspiration, PET) is defined as the rate of evapotranspiration from a large area covered by green grass which grows actively, completely shades the ground and which is not short of water. The rate of water which evapotranspires depends on the climate. The highest value of  $E_{\text{to}}$  is found in areas which are hot, dry, windy and sunny whereas the lowest values are observed in areas where it is cool, humid and cloudy with little or no wind.

In many cases it will be possible to obtain estimates of  $E_{\text{to}}$  for the area of concern (or an area nearby with similar climatic conditions) from the Meteorological Service. However, where this is not possible, the values for  $E_{\text{to}}$  have to be calculated. Two easy methods will be explained below:

### a. Pan evaporation method

With this method,  $E_{\text{to}}$  can be obtained by using evaporation rates which are directly measured with an evaporation pan. This is a shallow pan, containing water which is exposed to the evaporative influence of the climate. The standard pan is the Class A Pan of the US Weather Bureau (Figure 6). It has a diameter of 1.21 m, a depth of 25 cm and is placed 15 cm above the ground.

**Figure 5 Class A evaporation pan**



An evaporation pan is easy to construct and in most situations the material can be found locally.

The principle of obtaining evaporation rates from the pan is as follows:

- the pan is installed in the field 15 cm above the ground;
- the pan is filled with water 5 cm below the rim;
- the water is allowed to evaporate during a certain period of time (usually 24 hours). For example, each morning at 7.00 hours a measurement is taken. Rainfall, if any, is measured simultaneously;
- after 24 hours, the water depth is measured again;
- the amount of water which has evaporated in a given time unit is equal to the difference between the two measured water depths. This is the pan evaporation rate: Epan (mm/24 hours).

The readings taken from the pan (Epan) however do not give ETo directly, but have to be multiplied by a "Pan Coefficient" (Kpan).

thus:  $E_{To} = E_{pan} \times K_{pan}$

For the Class A evaporation pan, Kpan varies between 0.35 and 0.85, with an average of 0.70. If the precise pan factor is not known, the average value (0.70) can be used as an approximation. For greater accuracy a detailed table of Kpan figures is given in Irrigation Water Management Training Manual No. 3.

#### b. The Blaney-Criddle Method

If no measured data on pan evaporation are available, the Blaney-Criddle method can be used to calculate ETo. This method is straightforward and requires only data on mean daily temperatures. However, with this method, only approximations of ETo are obtained which can be inaccurate in extreme conditions.

The Blaney-Criddle formula is:  $E_{To} = p(0.46T_{mean} + 8)$  where:

ETo = reference crop evapotranspiration (mm/day)

Tmean = mean daily temperature (° C)

p = mean daily percentage of annual daytime hours.

The Blaney-Criddle Method always refers to mean monthly values, both for the temperature and the ETo. If in a local meteorological station the daily minimum and maximum temperatures are measured, the mean daily temperature is calculated as follows:

$$T_{max} = \frac{\text{sum of all T max values during the month}}{\text{number of days of the month}}$$

$$T_{min} = \frac{\text{sum of all T min values during the month}}{\text{number of days of the month}}$$

$$T_{mean} = \frac{T_{max} + T_{min}}{2}$$

To determine the value of p, Table 8 is used. To be able to obtain the p value, it is essential to know the approximate latitude of the area: the number of degrees north or south of the Equator.

**Table 8 - MEAN DAILY PERCENTAGE (p) OF ANNUAL DAYTIME HOURS FOR DIFFERENT LATITUDES**

Latitude:												
North	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
South	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
60°	.15	.20	.26	.32	.38	.41	.40	.34	.28	.22	.17	.13
55	.17	.21	.26	.32	.36	.39	.38	.33	.28	.23	.18	.16
50	.19	.23	.27	.31	.34	.36	.35	.32	.28	.24	.20	.18
45	.20	.23	.27	.30	.34	.35	.34	.32	.28	.24	.21	.20
40	.22	.24	.27	.30	.32	.34	.33	.31	.28	.25	.22	.21
35	.23	.25	.27	.29	.31	.32	.32	.30	.28	.25	.23	.22
30	.24	.25	.27	.29	.31	.32	.31	.30	.28	.26	.24	.23
25	.24	.26	.27	.29	.30	.31	.31	.29	.28	.26	.25	.24
20	.25	.26	.27	.28	.29	.30	.30	.29	.28	.26	.25	.25
15	.26	.26	.27	.28	.29	.29	.29	.28	.28	.27	.26	.25
10	.26	.27	.27	.28	.28	.29	.29	.28	.28	.27	.26	.26
5	.27	.27	.27	.28	.28	.28	.28	.28	.28	.27	.27	.27
0	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27

For example, when  $p = 0.29$  and  $T \text{ mean} = 21.5 \text{ }^\circ\text{C}$ , the  $E_{To}$  is calculated as follows:  
 $E_{To} = 0.29 (0.46 \times 21.5 + 8) = 0.29 (9.89 + 8) = 0.29 \times 17.89 = 5.2 \text{ mm/day}$ .

**Table 9 - INDICATIVE VALUES OF  $E_{To}$  (mm/day)**

Climatic zone	Mean daily temperature		
	15°	15-25°C	25°
Desert/arid	4-6	7-8	9-10
Semi-arid	4-5	6-7	8-9
Sub-humid	3-4	5-6	7-8
Humid	1-2	3-4	5-6

c. Indicative values of  $E_{To}$

Table 9 contains approximate values for  $E_{To}$  which may be used in the absence of measured or calculated figures.

iii. Crop Factor -  $K_c$

In order to obtain the crop water requirement  $ET_{crop}$  the reference crop evapotranspiration,  $ET_o$ , must be multiplied by the crop factor,  $K_c$ . The crop factor (or "crop coefficient") varies according to the growth stage of the crop. There are four growth stages to distinguish:

- the initial stage: when the crop uses little water;
- the crop development stage, when the water consumption increases;
- the mid-season stage, when water consumption reaches a peak;
- the late-season stage, when the maturing crop once again requires less water.

Table 10 contains crop factors for the most commonly crops grown under water harvesting.

**Table 10 - CROP FACTORS ( $K_c$ )**

Crop	Initial stage	(days)	Crop dev. Stage	(days)	Mid-season stage	(days)	Late season	(days)	Season average.
Cotton	0.45	(30)	0.75	(50)	1.15	(55)	0.75	(45)	0.82
Maize	0.40	(20)	0.80	(35)	1.15	(40)	0.70	(30)	0.82
Millet	0.35	(15)	0.70	(25)	1.10	(40)	0.65	(25)	0.79
Sorghum	0.35	(20)	0.75	(30)	1.10	(40)	0.65	(30)	0.78
Grain/small	0.35	(20)	0.75	(30)	1.10	(60)	0.65	(40)	0.78
Legumes	0.45	(15)	0.75	(25)	1.10	(35)	0.50	(15)	0.79
Groundnuts	0.45	(25)	0.75	(35)	1.05	(45)	0.70	(25)	0,79

Table 10 also contains the number of days which each crop takes over a given growth stage. However, the length of the different crop stages will vary according to the variety and the climatic conditions where the crop is grown. In the semi-arid/arid areas where WH is practised crops will often mature faster than the figures quoted in Table 10.

#### iv. Calculation of $ET_{crop}$

While conventional irrigation strives to maximize the crop yields by applying the optimal amount of water required by the crops at well determined intervals, this is not possible with water harvesting techniques. As already discussed, the farmer or agropastoralist has no influence on the occurrence of the rains neither in time nor in the amount of rainfall.

Bearing the above in mind, it is therefore a common practice to only determine the total amount of water which the crop requires over the whole growing season. As explained in section 2.1.4, the crop water requirement for a given crop is calculated according to the formula:

$$ET_{crop} = K_c \times ET_o$$

Since the values for  $ET_o$  are normally measured or calculated on a daily basis (mm/day), an average value for the total growing season has to be determined and then multiplied with the average seasonal crop factor  $K_c$  as given in the last column of Table 10.

Example:

Crop to be grown: Sorghum

- length of total growing season: 120 days (sum of all 4 crop stages according to Table 10)

- ETo: average of 6.0 mm/day over the total growing season (from measurement, calculation or Table 9)

Crop water Requirement:

ET crop =  $k_c \times E_{to}$

ET crop =  $0.78 \times 6 = 4.68$  mm per day

ET crop =  $4.68 \times 120$  days = approx. 560 mm per total growing season

## 2.2 Water requirements of trees, rangeland and fodder

### 2.2.1 Multipurpose trees

There is little information available about the water requirements of multipurpose trees planted under rainwater harvesting systems in semi-arid areas. In general, the water requirements for trees are more difficult to determine than for crops. Trees are relatively sensitive to moisture stress during the establishment stage compared with their ability to withstand drought once their root systems are fully developed. There is no accurate information available on the response of these species, in terms of yields, to different irrigation/water regimes.

Table 11 gives some basic data of multipurpose trees often planted in semi-arid areas. The critical stage for most trees is in the first two years of seedling/sapling establishment.

**Table 11 - NATURALLY PREFERRED CLIMATIC ZONES OF MULTIPURPOSE TREES**

	Semi-arid/marginal 500-900 mm rain	Arid/semi-arid 150-500 mm rain	Tolerance to temporary waterlogging
Acacia albida	yes	yes	yes
A. nilotica	yes	yes	yes
A. saligna	no	yes	yes
A. senegal	yes	yes	no
A. seyal	yes	yes	yes
A. tortilis	yes	yes	no
Albizia lebbeck	yes	no	no
Azadirachta indica	yes	no	some

Balanites aegyptiaca	yes	yes	yes
Cassia siamea	yes	no	no
Casuarina equisetifolia	yes	no	some
Colophospermum mopane	yes	yes	yes
Cordeauxia edulis	no	yes	?
Cordia sinensis	no	yes	?
Delonix elata	yes	no	?
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

Table 11 is based on the ICRAF Publication "Agroforestry in Dryland Africa", Rocheleau *et al.* (1988).

### 2.2.2 Fruit trees

There are some known values of water requirements for fruit trees under water harvesting systems - most of the figures have been derived from Israel. Table 12 contains the water requirements for some fruit trees.

**Table 12 - FRUIT TREE WATER REQUIREMENTS**

Species	Seasonal water requirement	Place	Source
Apricots	550 mm*	Israel	Finkel (1988, quoting Evanari <i>et al.</i> )
Peaches	700 mm*	Israel	Finkel (1988, quoting Evanari <i>et al.</i> )
Pomegranate	265 mm	Israel	Shanan and Tadmor (1979)
Jujube (Ziziphus mauritiana)	550-750 mm	India	Sharma <i>et al.</i> (1986)

\* This figure is the full irrigation rate. Where there was no irrigation but only rainwater harvesting the equivalent of 270 mm depth was adequate to support the trees.

### **2.2.3 Water requirements of rangeland and fodder**

Water requirements for rangeland and fodder species grown in semi-arid/arid areas under WH systems are usually not calculated.

The objective is to improve performance, within economic constraints, and to ensure the survival of the plants from season to season, rather than fully satisfying water requirements.

## **2.3 Soil requirements for water harvesting**

### **2.3.1 Introduction**

The physical, chemical and biological properties of the soil affect the yield response of plants to extra moisture harvested. Generally the soil characteristics for water harvesting should be the same as those for irrigation.

Ideally the soil in the catchment area should have a high runoff coefficient while the soil in the cultivated area should be a deep, fertile loam. Where the conditions for the cultivated and catchment areas conflict, the requirements of the cultivated area should always take precedence.

The following are important aspects of soils which affect plant performance under WH systems.

### **2.3.2 Texture**

The texture of a soil has an influence on several important soil characteristics including infiltration rate and available water capacity. Soil texture refers to its composition in terms of mineral particles. A broad classification is:

- a. Coarse textured soils - sand predominant - "sandy soils"
- b. Medium textured soils - silt predominant - "loamy soils"
- c. Fine textured soils - clay predominant - "clayey soils"

Generally speaking it is the medium textured soils, the loams, which are best suited to WH system since these are ideally suited for plant growth in terms of nutrient supply, biological activity and nutrient and water holding capacities.

### **2.3.3 Structure**

Soil structure refers to the grouping of soil particles into aggregates, and the arrangement of these aggregates. A good soil structure is usually associated with loamy soil and a relatively high content of organic matter. Inevitably, under hot climatic conditions, organic matter levels are often low, due to the rapid rates of decomposition. The application of organic materials such as crop residues and animal manure is helpful in improving the structure.

### **2.3.4 Depth**

The depth of soil is particularly important where WH systems are proposed. Deep soils have the capacity to store the harvested runoff as well as providing a greater amount of

total nutrients for plant growth. Soils of less than one metre deep are poorly suited to WH. Two metres depth or more is ideal, though rarely found in practice.

### 2.3.5 Fertility

In many of the areas where WH systems may be introduced, lack of moisture and low soil fertility are the major constraints to plant growth. Some areas in Sub-Saharan Africa, for example, may be limited by low soil fertility as much as by lack of moisture. Nitrogen and phosphorus are usually the elements most deficient in these soils. While it is often not possible to avoid poor soils in areas under WH system development, attention should be given to the maintenance of fertility levels.

### 2.3.6 Salinity/sodicity

Sodic soils, which have a high exchangeable sodium percentage, and saline soil which have excess soluble salts, should be avoided for WH systems. These soils can reduce moisture availability directly, or indirectly, as well as exerting direct harmful influence on plant growth.

### 2.3.7 Infiltration rate

The infiltration rate of a soil depends primarily on its texture. Typical comparative figures of infiltration are as follows:

	mm/hour
sandy soil	50
sandy loam	25
loam	12.5
clay loam	7.5

A very low infiltration rate can be detrimental to WH systems because of the possibility of waterlogging in the cultivated area. On the other hand, a low infiltration rate leads to high runoff, which is desirable for the catchment area. The soils of the cropped area however should be sufficiently permeable to allow adequate moisture to the crop root zone without causing waterlogging problems. Therefore, the requirements of the cultivated area should always take precedence.

Crust formation is a special problem of arid and semi-arid areas, leading to high runoff and low infiltration rates. Soil compaction as a result of heavy traffic either from machinery or grazing animals could also result in lower infiltration rates.

### 2.3.8 Available water capacity (AWC)

The capacity of soils to hold, and to release adequate levels of moisture to plants is vital to WH. AWC is a measure of this parameter, and is expressed as the depth of water in mm readily available to plants after a soil has been thoroughly wetted to "field capacity". AWC values for loams vary from 100-200 mm/metre. Not only is the AWC important, but the depth of the soil is critical also. In WH systems which pond runoff, it is vital that this water can be held by the soil and made available to the plants.

The AWC has implications for technical design - for example simple calculation demonstrates that even in deep soils (2 metres) with high AWC values (200 mm/metre) there is no point ponding water to depths greater than 40 cm. This quantity when infiltrated is adequate to replenish the soil profile from permanent wilting point to field capacity and any surplus will be lost by deep drainage as well as being a potential waterlogging hazard.

### **2.3.9 Constructional characteristics**

The ability of a soil to form resilient earth bunds (where these are a component of the WH system) is very important, and often overlooked. Generally the soils which should particularly be avoided are those which crack on drying, namely those which contain a high proportion of montmorillonite clay (especially vertisols or "black cotton soils"), and those which form erodible bunds, namely very sandy soils, or soils with very poor structure.

## **3. Rainfall-runoff analysis**

### **3.1 Introduction**

As defined in Chapter 1, water harvesting is the collection of runoff for productive use.

Runoff is generated by rainstorms and its occurrence and quantity are dependent on the characteristics of the rainfall event, i.e. intensity, duration and distribution. There are, in addition, other important factors which influence the runoff generating process. They will be discussed in section 3.5.

### **3.2 Rainfall characteristics**

Precipitation in arid and semi-arid zones results largely from convective cloud mechanisms producing storms typically of short duration, relatively high intensity and limited areal extent. However, low intensity frontal-type rains are also experienced, usually in the winter season. When most precipitation occurs during winter, as in Jordan and in the Negev, relatively low-intensity rainfall may represent the greater part of annual rainfall.

Rainfall intensity is defined as the ratio of the total amount of rain (rainfall depth) falling during a given period to the duration of the period. It is expressed in depth units per unit time, usually as mm per hour (mm/h).

The statistical characteristics of high-intensity, short-duration, convective rainfall are essentially independent of locations within a region and are similar in many parts of the world. Analysis of short-term rainfall data suggests that there is a reasonably stable relationship governing the intensity characteristics of this type of rainfall. Studies carried out in Saudi Arabia (Raikes and Partners 1971) suggest that, on average, around 50 percent of all rain occurs at intensities in excess of 20 mm/hour and 20-30 percent occurs at intensities in excess of 40 mm/hour. This relationship appears to be independent of the long-term average rainfall at a particular location.

### **3.3 Variability of annual rainfall**

Water harvesting planning and management in arid and semi-arid zones present difficulties which are due less to the limited amount of rainfall than to the inherent degree of variability associated with it.

In temperate climates, the standard deviation of annual rainfall is about 10-20 percent and in 13 years out of 20, annual amounts are between 75 and 125 percent of the mean. In arid and semi-arid climates the ratio of maximum to minimum annual amounts is much greater and the annual rainfall distribution becomes increasingly skewed with increasing aridity. With mean annual rainfalls of 200-300 mm the rainfall in 19 years out of 20 typically ranges from 40 to 200 percent of the mean and for 100 mm/year, 30 to 350 percent of the mean. At more arid locations it is not uncommon to experience several consecutive years with no rainfall.

For a water harvesting planner, the most difficult task is therefore to select the appropriate "design" rainfall according to which the ratio of catchment to cultivated area will be determined (see Chapter 4).

Design rainfall is defined as the total amount of rain during the cropping season at which or above which the catchment area will provide sufficient runoff to satisfy the crop water requirements. If the actual rainfall in the cropping season is below the design rainfall, there will be moisture stress in the plants; if the actual rainfall exceeds the design rainfall, there will be surplus runoff which may result in a damage to the structures.

The design rainfall is usually assigned to a certain probability of occurrence or exceedance. If, for example, the design rainfall with a 67 percent probability of exceedance is selected, this means that on average this value will be reached or exceeded in two years out of three and therefore the crop water requirements would also be met in two years out of three.

The design rainfall is determined by means of a statistical probability analysis.

### 3.4 Probability analysis

A rather simple, graphical method to determine the probability or frequency of occurrence of yearly or seasonal rainfall will be described in this chapter. For the design of water harvesting schemes, this method is as valid as any analytical method described in statistical textbooks.

The first step is to obtain annual rainfall totals for the cropping season from the area of concern. In locations where rainfall records do not exist, figures from stations nearby may be used with caution. It is important to obtain long-term records. As explained in section 3.2, the variability of rainfall in arid and semi-arid areas is considerable. An analysis of only 5 or 6 years of observations is inadequate as these 5 or 6 values may belong to a particularly dry or wet period and hence may not be representative for the long term rainfall pattern.

In the following example, 32 annual rainfall totals from Mogadishu (Somalia) were used for an analysis (Table 13).

**Table 13 - ANNUAL RAINFALL, MOGADISHU (SOMALIA)**

Year	R mm	Year	R mm	Year	R mm	Year	R mm	Year	R mm

1957	484	1964	489	1971	271	1977	660	1983	273
1958	529	1965	498	1972	655	1978	216	1984	270
1959	302	1966	395	1973	371	1979	594	1985	423
1960	403	1967	890	1974	255	1980	544	1986	251
1961	960	1968	680	1975	411	1981	563	1987	533
1962	453	1969	317	1976	339	1982	526	1988	531
1963	633	1970	300						

The next step is to rank the annual totals from Table 13 with m = 1 for the largest and m = 32 for the lowest value and to rearrange the data accordingly (Table 14).

The probability of occurrence P (%) for each of the ranked observations can be calculated (columns 4, 8, 12, 16, Table 14) from the equation:

$$P(\%) = \frac{m - 0.375}{N + 0.25} \times 100$$

where:

P = probability in % of the observation of the rank m

m = the rank of the observation

N = total number of observations used

**Table 14 - RANKED ANNUAL RAINFALL DATA, MOGADISHU (SOMALIA)**

Year	R	m	P	Year	R	m	P	Year	R	m	P	Year	R	m	P
	m		%		m		%		m		%		m		%
	m		%		m		%		m		%		m		%
1961	960	1	1.9	1988	531	11	32.9	1966	395	21	64.0	1986	251	31	95.0
1967	890	2	5.0	1958	529	12	36.0	1973	371	22	67.1	1978	216	32	98.1
1968	680	3	8.1	1982	526	13	39.1	1976	339	23	70.2				
1977	660	4	11.2	1965	498	14	42.2	1969	317	24	73.3				
1972	655	5	14.3	1964	489	15	45.3	1959	302	25	76.4				
1963	633	6	17.4	1957	484	16	48.4	1970	300	26	79.5				

1979	594	7	20. 5	196 2	453	17	51. 6	198 3	273	27	82. 6				
1981	563	8	23. 6	198 5	423	18	54. 7	197 1	271	28	85. 7				
1980	544	9	26. 7	197 5	411	19	57. 8	198 4	270	29	88. 8				
1987	533	1 0	29. 8	196 0	403	20	60. 9	197 4	255	30	91. 1				

The above equation is recommended for N = 10 to 100 (Reining **et al.** 1989). There are several other, but similar, equations known to compute experimental probabilities.

The next step is to plot the ranked observations (columns 2, 6, 10, 14, Table 14) against the corresponding probabilities (columns 4, 8, 12, 16, Table 14). For this purpose normal probability paper must be used.

Finally a curve is fitted to the plotted observations in such a way that the distance of observations above or below the curve should be as close as possible to the curve. The curve may be a straight line.

From this curve it is now possible to obtain the probability of occurrence or exceedance of a rainfall value of a specific magnitude. Inversely, it is also possible to obtain the magnitude of the rain corresponding to a given probability.

In the above example, the annual rainfall with a probability level of 67 percent of exceedance is 371 mm (Figure 7), i.e. on average in 67 percent of time (2 years out of 3) annual rain of 371 mm would be equalled or exceeded.

For a probability of exceedance of 33 percent, the corresponding value of the yearly rainfall is 531 mm.

The return period T (in years) can easily be derived once the exceedance probability P (%) is known from the equations.

$$T = \frac{100}{P} \text{(years)}$$

From the above examples the return period for the 67 percent and the 33 percent exceedance probability events would thus be:

$$T_{67\%} = \frac{100}{67} = 1.5 \text{(years)}$$

i.e. on average an annual rainfall of 371 mm or higher can be expected in 2 years out of 3;

$$T_{33\%} = \frac{100}{33} = 3 \text{(years)}$$

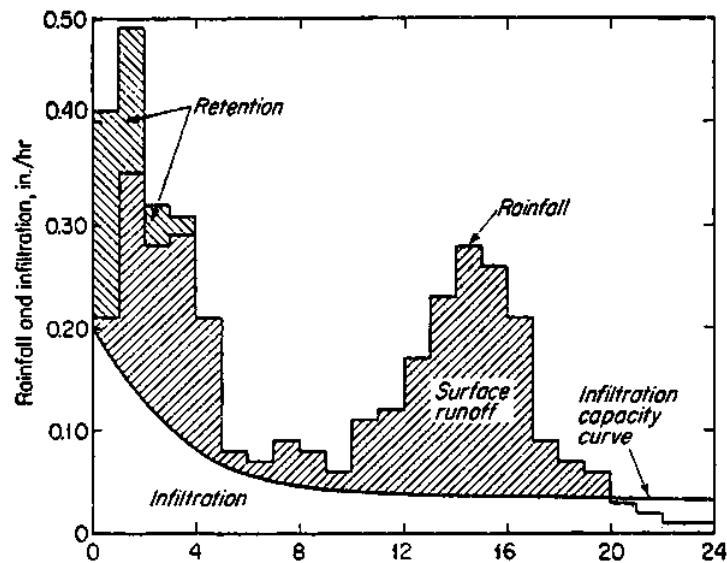
respectively i.e. on average an annual rainfall of 531 mm or more can only be expected in 1 year out of 3.

### 3.5 Rainfall-runoff relationship

#### 3.5.1 The surface runoff process

When rain falls, the first drops of water are intercepted by the leaves and stems of the vegetation. This is usually referred to as interception storage.

**Figure 6 Schematic diagram illustrating relationship between rainfall, infiltration and runoff (Source: Linsley et al. 1958)**



As the rain continues, water reaching the ground surface infiltrates into the soil until it reaches a stage where the rate of rainfall (intensity) exceeds the infiltration capacity of the soil. Thereafter, surface puddles, ditches, and other depressions are filled (depression storage), after which runoff is generated.

The infiltration capacity of the soil depends on its texture and structure, as well as on the antecedent soil moisture content (previous rainfall or dry season). The initial capacity (of a dry soil) is high but, as the storm continues, it decreases until it reaches a steady value termed as final infiltration rate (see Figure 6).

The process of runoff generation continues as long as the rainfall intensity exceeds the actual infiltration capacity of the soil but it stops as soon as the rate of rainfall drops below the actual rate of infiltration.

The rainfall runoff process is well described in the literature. Numerous papers on the subject have been published and many computer simulation models have been developed. All these models, however, require detailed knowledge of a number of factors and initial boundary conditions in a catchment area which in most cases are not readily available.

For a better understanding of the difficulties of accurately predicting the amount of runoff resulting from a rainfall event, the major factors which influence the rainfall-runoff process are described below.

### 3.5.2 Factors affecting runoff

Apart from rainfall characteristics such as intensity, duration and distribution, there are a number of site (or catchment) specific factors which have a direct bearing on the occurrence and volume of runoff.

#### i. Soil type

The infiltration capacity is among others dependent on the porosity of a soil which determines the water storage capacity and affects the resistance of water to flow into deeper layers.

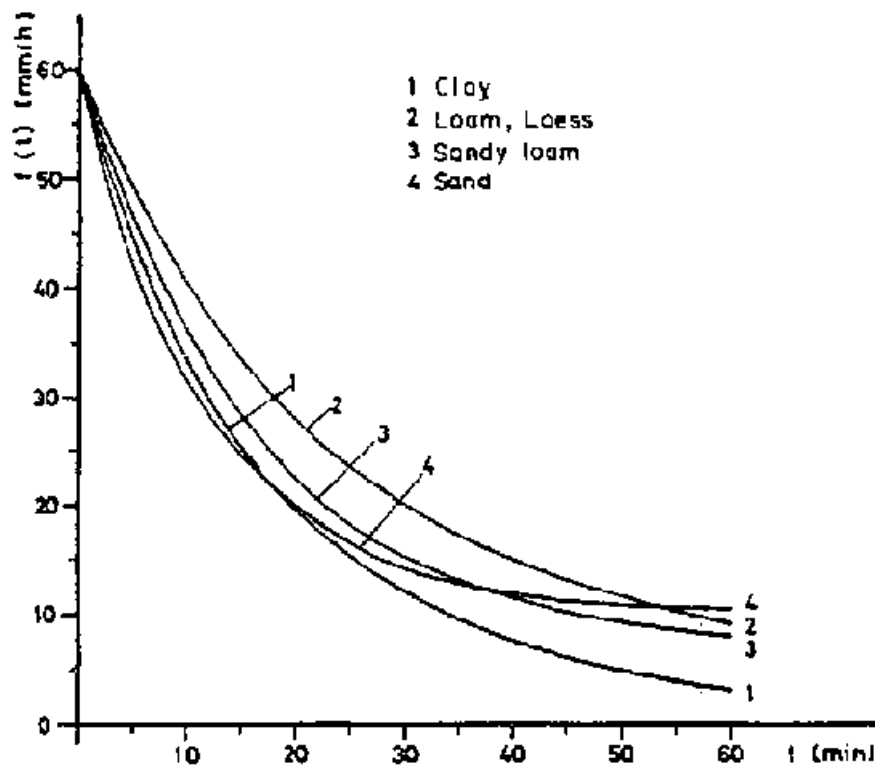
Porosity differs from one soil type to the other. The highest infiltration capacities are observed in loose, sandy soils while heavy clay or loamy soils have considerable smaller infiltration capacities.

Figure 9 illustrates the difference in infiltration capacities measured in different soil types.

The infiltration capacity depends furthermore on the moisture content prevailing in a soil at the onset of a rainstorm.

The initial high capacity decreases with time (provided the rain does not stop) until it reaches a constant value as the soil profile becomes saturated (Figures 8 and 9).

**Figure 7 Infiltration capacity curves for different soil types**



This however, is only valid when the soil surface remains undisturbed.

It is well known that the average size of raindrops increases with the intensity of a rainstorm. In a high intensity storm the kinetic energy of raindrops is considerable when hitting the soil surface. This causes a breakdown of the soil aggregate as well as soil dispersion with the consequence of driving fine soil particles into the upper soil pores. This results in clogging of the pores, formation of a thin but dense and compacted layer at the surface which highly reduces the infiltration capacity.

This effect, often referred to as capping, crusting or sealing, explains why in arid and semi-arid areas where rainstorms with high intensities are frequent, considerable quantities of surface runoff are observed even when the rainfall duration is short and the rainfall depth is comparatively small.

Soils with a high clay or loam content (e.g. Loess soils with about 20% clay) are the most sensitive for forming a cap with subsequently lower infiltration capacities. On coarse, sandy soils the capping effect is comparatively small.

#### ii. Vegetation

The amount of rain lost to interception storage on the foliage depends on the kind of vegetation and its growth stage. Values of interception are between 1 and 4 mm. A cereal crop, for example, has a smaller storage capacity than a dense grass cover.

More significant is the effect the vegetation has on the infiltration capacity of the soil. A dense vegetation cover shields the soil from the raindrop impact and reduces the crusting effect as described earlier.

In addition, the root system as well as organic matter in the soil increase the soil porosity thus allowing more water to infiltrate. Vegetation also retards the surface flow particularly on gentle slopes, giving the water more time to infiltrate and to evaporate.

In conclusion, an area densely covered with vegetation, yields less runoff than bare ground.

#### iii. Slope and catchment size

Investigations on experimental runoff plots (Sharma **et al.** 1986) have shown that steep slope plots yield more runoff than those with gentle slopes.

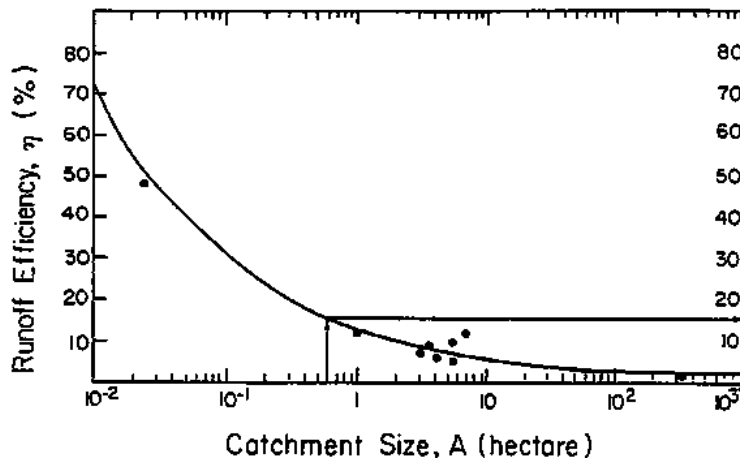
In addition, it was observed that the quantity of runoff decreased with increasing slope length.

This is mainly due to lower flow velocities and subsequently a longer time of concentration (defined as the time needed for a drop of water to reach the outlet of a catchment from the most remote location in the catchment). This means that the water is exposed for a longer duration to infiltration and evaporation before it reaches the measuring point. The same applies when catchment areas of different sizes are compared.

The runoff efficiency (volume of runoff per unit of area) increases with the decreasing size of the catchment i.e. the larger the size of the catchment the larger the time of concentration and the smaller the runoff efficiency.

Figure 10 clearly illustrates this relationship.

Figure 8. Runoff efficiency as a function of catchment size (Ben Asher 1988)



It should however be noted that the diagram in Figure 8 has been derived from investigations in the Negev desert and not be considered as generally applicable to others regions. The purpose of this diagram is to demonstrate the general trend between runoff and catchment size.

### 3.5.3 Runoff coefficients

Apart from the above-mentioned site-specific factors which strongly influence the rainfall-runoff process, it should also be considered that the physical conditions of a catchment area are not homogenous. Even at the micro level there are a variety of different slopes, soil types, vegetation covers etc. Each catchment has therefore its own runoff response and will respond differently to different rainstorm events.

The design of water harvesting schemes requires the knowledge of the quantity of runoff to be produced by rainstorms in a given catchment area. It is commonly assumed that the quantity (volume) of runoff is a proportion (percentage) of the rainfall depth.

$$\text{Runoff [mm]} = K \times \text{Rainfall depth [mm]}$$

In rural catchments where no or only small parts of the area are impervious, the coefficient  $K$ , which describes the percentage of runoff resulting from a rainstorm, is however not a constant factor. Instead its value is highly variable and depends on the above described catchment-specific factors and on the rainstorm characteristics.

For example, in a specific catchment area with the same initial boundary condition (e.g. antecedent soil moisture), a rainstorm of 40 minutes duration with an average intensity of 30 mm/h would produce a smaller percentage of runoff than a rainstorm of only 20 minutes duration but with an average intensity of 60 mm/h although the total rainfall depth of both events were equal.

### 3.6 Determination of runoff coefficients

For reasons explained before, the use of runoff coefficients which have been derived for watersheds in other geographical locations should be avoided for the design of a water harvesting scheme. Also runoff coefficients for large watersheds should not be applied to small catchment areas.

An analysis of the rainfall-runoff relationship and subsequently an assessment of relevant runoff coefficients should best be based on actual, simultaneous measurements of both rainfall and runoff in the project area.

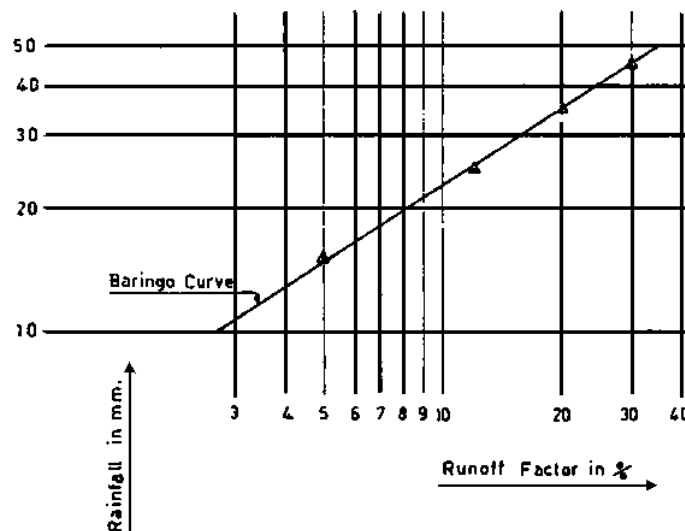
As explained above, the runoff coefficient from an individual rainstorm is defined as runoff divided by the corresponding rainfall both expressed as depth over catchment area (mm):

$$K = \frac{\text{Runoff [mm]}}{\text{Rainfall [mm]}}$$

Actual measurements should be carried out until a representative range is obtained. Shanani and Tadmor recommend that at least 2 years should be spent to measure rainfall and runoff data before any larger construction programme starts. Such a time span would in any case be justified bearing in mind the negative demonstration effect a water harvesting project would have if the structures were seriously damaged or destroyed already during the first rainstorm because the design was based on erroneous runoff coefficients.

When plotting the runoff coefficients against the relevant rainfall depths a satisfactory correlation is usually observed (see Figure 9).

**Figure 9. Rainfall-runoff relationships, Baringo, Kenya (Source: Finkel 1987)**



A much better relationship would be obtained if in addition to rainfall depth the corresponding rainstorm intensity, the rainstorm duration and the antecedent soil moisture were also measured. This would allow rainstorm events to be grouped according to their average intensity and their antecedent soil moisture and to plot the runoff coefficients against the relevant rainfall durations separately for different intensities.

Rainfall intensities can be accurately measured by means of a continuously recording autographic rain gauge.

It is also possible to time the length of individual rainstorms and to calculate the average intensities by dividing the measured rainfall depths by the corresponding duration of the storms.

When analysing the measured data it will be noted that a certain amount of rainfall is always required before any runoff occurs. This amount, usually referred to as threshold rainfall, represents the initial losses due to interception and depression storage as well as to meet the initially high infiltration losses.

The threshold rainfall depends on the physical characteristics of the area and varies from catchment to catchment. In areas with only sparse vegetation and where the land is very regularly shaped, the threshold rainfall may be only in the range of 3 mm while in other catchments this value can easily exceed 12 mm, particularly where the prevailing soils have a high infiltration capacity. The fact that the threshold rainfall has first to be surpassed explains why not every rainstorm produces runoff. This is important to know when assessing the annual runoff-coefficient of a catchment area.

### **3.7 Assessment of annual or seasonal runoff**

The knowledge of runoff from individual storms as described before is essential to assess the runoff behaviour of a catchment area and to obtain an indication both of runoff-peaks which the structure of a water harvesting scheme must withstand and of the needed capacity for temporary surface storage of runoff, for example the size of an infiltration pit in a microcatchment system.

However, to determine the ratio of catchment to cultivated area, as described in chapter 4, it is necessary to assess either the annual (for perennial crops) or the seasonal runoff coefficient. This is defined as the total runoff observed in a year (or season) divided by the total rainfall in the same year (or season).

$$K = \frac{\text{Yearly(seasonal)TotalRunoff[mm]}}{\text{Yearly(seasonal)TotalRainfall[mm]}}$$

The annual (seasonal) runoff coefficient differs from the runoff coefficients derived from individual storms as it takes into account also those rainfall events which did not produce any runoff. The annual (seasonal) runoff-coefficient is therefore always smaller than the arithmetic mean of runoff coefficients derived from individual runoff-producing storms.

### **3.8 Runoff plots**

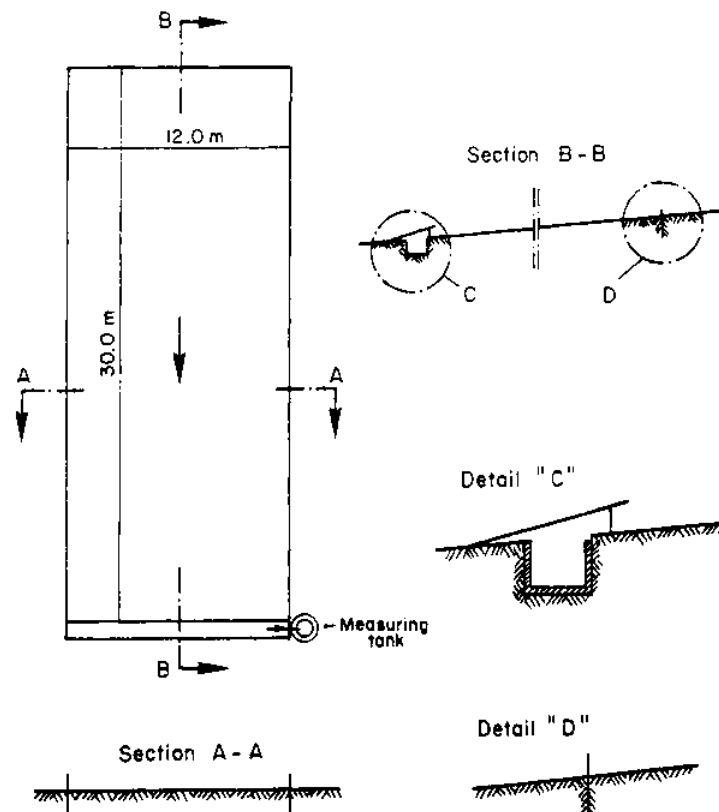
Runoff plots are used to measure surface runoff under controlled conditions. The plots should be established directly in the project area. Their physical characteristics, such as soil type, slope and vegetation must be representative of the sites where water harvesting schemes are planned.

The size of a plot should ideally be as large as the estimated size of the catchment planned for the water harvesting project. This is not always possible mainly due to the problem of storing the accumulated runoff. A minimum size of 3-4 m in width and 10-12 m in length is recommended. Smaller dimensions should be avoided, since the results obtained from very small plots are rather misleading.

Care must be taken to avoid sites with special problems such as rills, cracks or gullies crossing the plot. These would drastically affect the results which would not be representative for the whole area. The gradient along the plot should be regular and free of local depressions. During construction of the plot, care must be taken not to disturb or change the natural conditions of the plot such as destroying the vegetation or compacting the soil. It is advisable to construct several plots in series in the project area which would permit comparison of the measured runoff volumes and to judge on the representative character of the selected plot sites.

Around the plots metal sheets or wooden planks must be driven into the soil with at least 15 cm of height above ground to stop water flowing from outside into the plot and vice versa (see Figure 10). A rain gauge must be installed near to the plot. At the lower end of the plot a gutter is required to collect the runoff. The gutter should have a gradient of 1% towards the collection tank. The soil around the gutter should be backfilled and compacted. The joint between the gutter and the lower side of the plot may be cemented to form an apron in order to allow a smooth flow of water from the plot into the gutter. The collection tank may be constructed from stone masonry, brick or concrete blocks, but a buried barrel will also meet the requirements. The tank should be covered and thus be protected against evaporation and rainfall. The storage capacity of the tank depends on the size of the plot but should be large enough to collect water also from extreme rain storms. Following every storm (or every day at a specific time), the volume of water collected in the rain gauge and in the runoff tank must be measured. Thereafter the gauge and tank must be completely emptied. Any silt which may have deposited in the tank and in the gutter must be cleared.

**Figure 10. Standard layout of a runoff plot (Source: Siegert 1978)**



## 4. Design model for catchment: Cultivated area ratio

### 4.1 Introduction

Each WH system consists of a catchment (collection) and a cultivated (concentration) area. The relationship between the two, in terms of size, determines by what factor the rainfall will be "multiplied". For an appropriate design of a system, it is recommended to determine the ratio between catchment (C) and cultivated (CA) area.

Many successful water harvesting systems have been established by merely estimating the ratio between catchment and cultivated area. This may indeed be the only possible approach where basic data such as rainfall, runoff and crop water requirements are not known. However, calculation of the ratio will certainly result in a more efficient and effective system provided the basic data are available and accurate.

Nevertheless, it should be noted that calculations are always based on parameters with high variability. Rainfall and runoff are characteristically erratic in regions where WH is practised. It is, therefore, sometimes necessary to modify an original design in the light of experience, and often it will be useful to incorporate safety measures, such as cut-off drains, to avoid damage in years when rainfall exceeds the design rainfall.

The calculation of C:CA ratio is primarily useful for WH systems where crops are intended to be grown. This will be discussed first.

### 4.2 Crop production systems

The calculation of the catchment: cultivated area ratio is based on the concept that the design must comply with the rule:

**WATER HARVESTED = EXTRA WATER REQUIRED**

The amount of water harvested from the catchment area is a function of the amount of runoff created by the rainfall on the area. This runoff, for a defined time scale, is calculated by multiplying a "design" rainfall with a runoff coefficient. As not all runoff can be efficiently utilized (because of deep percolation losses, etc.) it must be additionally multiplied with an efficiency factor.

**WATER HARVESTED = CATCHMENT AREA X DESIGN RAINFALL X RUNOFF  
COEFFICIENT X EFFICIENCY FACTOR**

The amount of water required is obtained by multiplying the size of the cultivated area with the net crop water requirements which is the total water requirement less the assumed "design" rainfall.

**EXTRA WATER REQUIRED = CULTIVATED AREA X (CROP WATER REQUIREMENT -  
DESIGN RAINFALL)**

By substitution in our original equation

**WATER HARVESTED = EXTRA WATER REQUIRED**

we obtain:

$$\text{CATCHMENT AREA} \times \text{DESIGN RAINFALL} \times \text{RUNOFF COEFF.} \times \text{EFF. FACTOR} = \text{CULTIVATED AREA} \times (\text{CROP WATER REQUIREMENT} - \text{DESIGN RAINFALL})$$

If this formula is rearranged we finally obtain:

$$\frac{\text{CROP WATER REQUIREMENT} - \text{DESIGN RAINFALL}}{\text{DESIGN RAINFALL} \times \text{RUNOFF COEFF.} \times \text{EFF. FACTOR}} = \frac{\text{CATCHMENT AREA}}{\text{CULTIVATED AREA}}$$

### **Crop Water Requirement**

Crop water requirement depends on the kind of crop and the climate of the place where it is grown. Estimates as given in Chapter 2 should be used when precise data are not available.

### **Design Rainfall**

The design rainfall is set by calculations or estimates (see Chapter 3). It is the amount of seasonal rain at which, or above which, the system is designed to provide enough runoff to meet the crop water requirement. If the rainfall is below the "design rainfall," there is a risk of crop failure due to moisture stress. When rainfall is above the "design", then runoff will be in surplus and may overtop the bunds.

Design rainfall is calculated at a certain probability of occurrence. If, for example, it is set at a 67% probability, it will be met or exceeded (on average) in two years out of three and the harvested rain will satisfy the crop water requirements also in two out of three years.

A conservative design would be based on a higher probability (which means a lower design rainfall), in order to make the system more "reliable" and thus to meet the crop water requirements more frequently. However the associated risk would be a more frequent flooding of the system in years where rainfall exceeds the design rainfall.

### **Runoff Coefficient**

This is the proportion of rainfall which flows along the ground as surface runoff. It depends amongst other factors on the degree of slope, soil type, vegetation cover, antecedent soil moisture, rainfall intensity and duration. The coefficient ranges usually between 0.1 and 0.5. When measured data are not available, the coefficient may be estimated from experience. However, this method should be avoided whenever possible (see Chapter 3).

### **Efficiency Factor**

This factor takes into account the inefficiency of uneven distribution of the water within the field as well as losses due to evaporation and deep percolation. Where the cultivated area is levelled and smooth the efficiency is higher. Microcatchment systems have higher efficiencies as water is usually less deeply ponded. Selection of the factor is left to the discretion of the designer based on his experience and of the actual technique selected. Normally the factor ranges between 0.5 and 0.75.

## **4.3 Examples on how to calculate the ratio C: Ca**

a. Example One

Climate: Arid

RWH System: External Catchment (e.g. trapezoidal bunds)

Crop Millet:

- Crop Water Requirement for Millet (total growing season) = 475 mm (low because rapid maturity)

- Design Rainfall (growing season) == 250 mm (at a probability level of P = 67%)

- Runoff Coefficient (seasonal) = 0.25 (low due to relatively long catchment and low slope)

- Efficiency Factor = 0.5 (general estimate for long slope technique)

$$\frac{C}{CA} = \frac{475 - 250}{250 \times 0.25 \times 0.5} = 7.2$$

i.e.: The catchment area must be 7.2 times larger than the cultivated area (in other words, the catchment: cultivated area ratio is 7.2:1)

Comment: The ratio is high, but the system is designed for a dry area with a low runoff coefficient assumed.

b. Example Two:

Climate: Semi-Arid

RWH System: External Catchment (e.g. trapezoidal bunds)

Crop: 110 day Sorghum

- Crop Water Requirement = 525 mm

- Design Rainfall = 375 mm (P = 67%)

- Runoff Coefficient = 0.25

- Efficiency Factor = 0.5

$$\frac{C}{CA} = \frac{525 - 375}{375 \times 0.25 \times 0.5} = 3.2$$

i.e: The catchment area must be 3.2 times larger than the cultivated area. In other words, the catchment: cultivated area ratio is 3.2:1.

Comment: A ratio of approximately 3:1 is common and widely appropriate.

c. Example Three:

Climate: Semi-Arid

RWH System: Microcatchment (e.g. contour ridges)

Crop: 110 day Sorghum

- Crop Water Requirement = 525 mm

- Design Rainfall = 310 mm (set at a probability level of P = 75% to give more reliability)

- Runoff Coefficient == 0.5 (reflecting the high proportion of runoff from very short catchments)

- Efficiency Factor == 0.75 (reflecting the greater efficiency of short slope catchments)

$$\frac{C}{CA} = \frac{525-310}{310 \times 0.75 \times 0.5} = 1.85$$

i.e. The catchment area must be approximately twice as large as the cultivated area.

Comment: Ratios are always lower for microcatchment systems due to a higher efficiency of water use and a higher runoff coefficient. Using a design rainfall of 67% probability (i.e. a less reliable system) would have even reduced the ratio to 1:1.

#### 4.4 Systems for trees

The ratio between catchment and cultivated area is difficult to determine for systems where trees are intended to be grown. As already discussed, only rough estimates are available for the water requirements of the indigenous, multi-purpose species commonly planted in WH systems. Furthermore, trees are almost exclusively grown in microcatchment systems where it is difficult to determine which proportion of the total area is actually exploited by the root zone bearing in mind the different stages of root development over the years before a seedling has grown into a mature tree.

In view of the above, it is therefore considered sufficient to estimate only the total size of the microcatchment (MC), that is the catchment and cultivated area (infiltration pit) together, for which the following formula can be used:

$$MC = RA \times \frac{WR - DR}{DR - K - EFF}$$

where:

MC = total size of microcatchment (m<sup>2</sup>)  
 RA = area exploited by root system (m<sup>2</sup>)  
 WR = water requirement (annual) (mm)  
 DR = design rainfall (annual) (mm)  
 K = runoff coefficient (annual)  
 EFF = efficiency factor

As a rule of thumb, it can be assumed that the area to be exploited by the root system is equal to the area of the canopy of the tree.

##### Example:

Semi-arid area, fruit tree grown in Negarim microcatchment

Annual water requirement (WR) = 1000 mm

Annual design rainfall (DR) = 350 mm

Canopy of mature tree (RA) = 10 m<sup>2</sup>

Runoff coefficient (K) = 0.5

Efficiency factor (EFF) = 0.5

Total size MC = 10 x {(1000-350)/(350 x 0.5 x 0.5)} = 84m<sup>2</sup>

Table 15 shows some examples of catchment and cultivated area sizes for several species. The range in dimensions is remarkable.

As a rule of thumb, for multipurpose trees in the arid/semi-arid regions, the size of the microcatchment per tree (catchment and cultivated area together) should range between

10 and 100 square metres, depending on the aridity of the area and the species grown. Flexibility can be introduced by planting more than one tree seedling within the system and removing surplus seedlings at a later stage if necessary.

#### 4.4 Systems for rangeland and fodder

In most cases it is not necessary to calculate the ratio C:CA for systems implementing fodder production and/or rangeland rehabilitation. As a general guideline, a ratio of 2:1 to 3:1 for microcatchments (which are normally used) is appropriate.

**Table 15 - DIMENSIONS OF CATCHMENTS AND CULTIVATED AREAS FOR TREE MICROCATCHMENTS**

Species	Country	Catchment Area (m2)	Cultivated Area (m2)	Source
Ziziphus mauritiana	Rajasthan, India	31.5-72	36	Sharma et al. (1986)
Pomegranate	Negev, Israel	160	16	Shanan & Tadmore (1979)
Almonds	Negev, Israel	250	10	Ben-Asher (1988)
Fodder/Fuelwood spp.	Baringo, Kenya	10-20*		Critchley & Reij (1989)
Fodder spp.	Turkana, Kenya	93.75*	6.25**	Barrow (in Rocheleu et al. (1988)
Fuelwood/multi-purpose spp.	Guesselbodi Forest, Niger	64*		Critchley & Reij (1989)
Fuelwood/multi-purpose spp.	Keita Valley, Niger	12	1.8	Critchley & Reij (1989)

\* No breakdown given between catchment and cultivated area/infiltration pit.

\*\* In a number of cases two trees planted within the same system.

## 5. Water harvesting techniques

### 5.1.1 Site and technique selection

#### 5.1.1 People's priorities

Before selecting a specific technique, due consideration must be given to the social and cultural aspects prevailing in the area of concern as they are paramount and will affect the success or failure of the technique implemented. This is particularly important in the arid and semi-arid regions of Africa and may help to explain the failure of so many projects that did not take into account the people's priorities. In arid and semi-arid Africa, most of the population has experienced basic subsistence regimes which resulted over

the centuries in setting priorities for survival. Until all higher priorities have been satisfied, no lower priority activities can be effectively undertaken.

In Chapter 7 of this Manual, socio-economic aspects are discussed. Along with checking the sequence of priorities, the planner must also consider alternate sources of water. These must be compared with water harvesting in cost and in the risk involved. The comparison must take into account the water quality required, operational and maintenance considerations as well as the initial cost. Where alternate water is of better quality, is cheaper to develop, easier to obtain or involves less risk, it should be given priority. An example of this is the development of springs or shallow wells for micro-scale irrigation, prior to water harvesting.

### **5.1.2 Basic technical criteria**

A water harvesting scheme will only be sustainable if it fits into the socio-economic context of the area as described in the previous chapter and also fulfills a number of basic technical criteria.

Figure 16 contains a flowchart with the basic technical selection criteria for the different water harvesting techniques.

**SLOPE:** The ground slope is a key limiting factor to water harvesting. Water harvesting is not recommended for areas where slopes are greater than 5% due to uneven distribution of run-off and large quantities of earthwork required which is not economical.

**SOILS:** Should have the main attributes of soils which are suitable for irrigation: they should be deep, not be saline or sodic and ideally possess inherent fertility. A serious limitation for the application of water harvesting are soils with a sandy texture. If the infiltration rate is higher than the rainfall intensity, no runoff will occur.

**COSTS:** The quantities of earth/stonework involved in construction directly affects the cost of a scheme or, if it is implemented on a self help basis, indicates how labour intensive its construction will be.

Figure 16 System selection

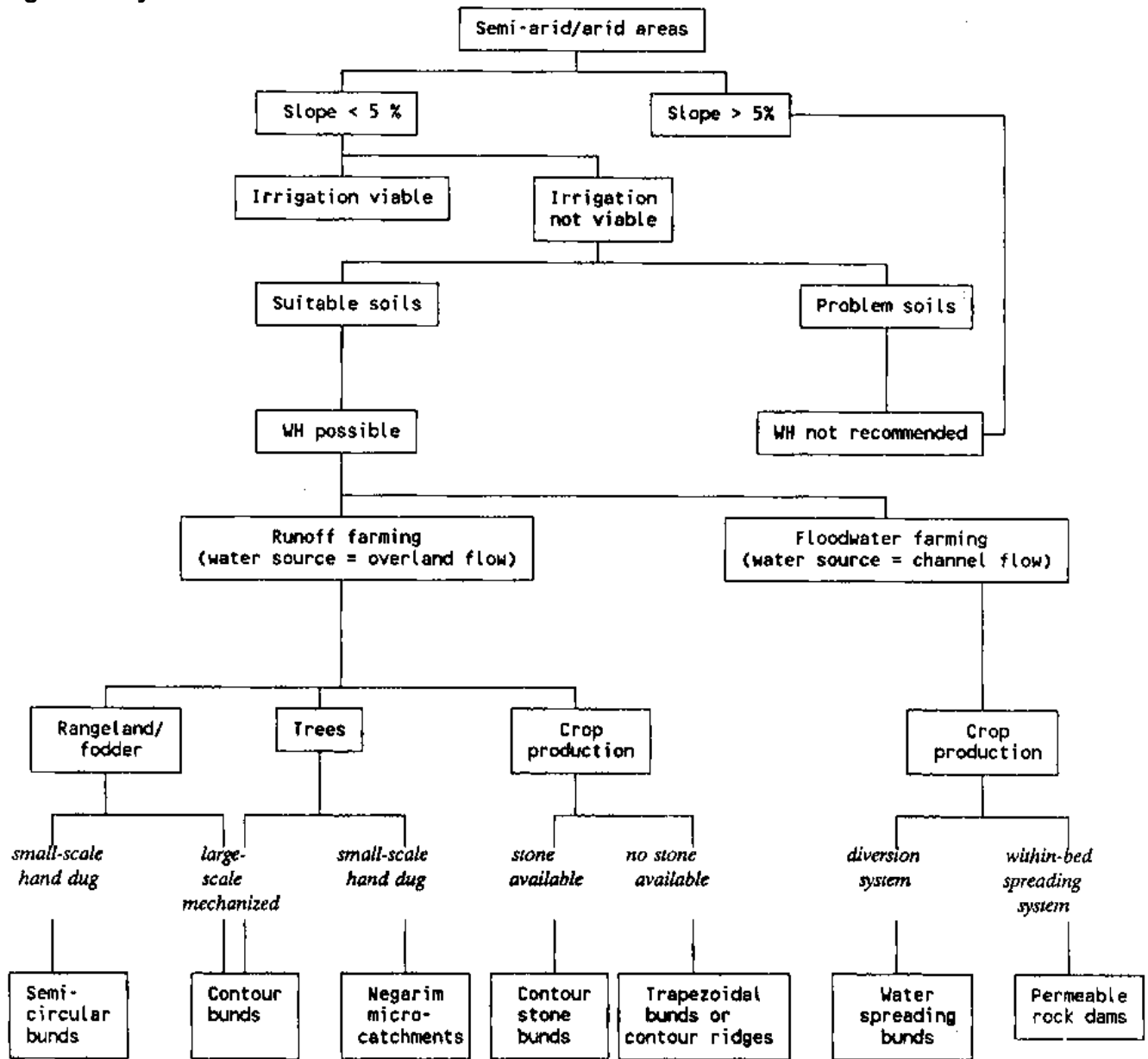


Table 16 can be used as a quick reference to check the quantity of necessary earthworks required for different systems. A more quantified breakdown is given in the following sections where each system is described in detail.

## 5.2 Negarim microcatchments

### 5.2.1 Background

Negarim microcatchments are diamond-shaped basins surrounded by small earth bunds with an infiltration pit in the lowest corner of each. Runoff is collected from within the basin and stored in the infiltration pit. Microcatchments are mainly used for growing trees

or bushes. This technique is appropriate for small-scale tree planting in any area which has a moisture deficit. Besides harvesting water for the trees, it simultaneously conserves soil. Negarim microcatchments are neat and precise, and relatively easy to construct.

**Table 16 - EARTHWORK/STONWORK FOR VARIOUS WATER HARVESTING SYSTEMS**

System Name and Number	Earthwork (m <sup>3</sup> /ha treated)						Stonework (m <sup>3</sup> /ha treated)	
	Negarim microcatchments (trees)	Contour bunds (trees)	Semi circular bunds (grass)	Contour ridges (crops)	Trapezoidal bunds (crops)	Water spreading bunds (crops)	Contour stone bunds (crops)	Permeable rock dams(crops)
Slope %	(1)	(2)	(3)	(4)	(5)	(8)	(6)	(7)
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

#### Notes

1. Typical dimensions are assumed for each system: for greater detail see relevant chapters.
2. For microcatchment systems (1, 2, 3 and 4), the whole area covered (cultivated and within-field catchment) is taken as "treated".
3. Labour rates for earthworks: Larger structures (e.g. trapezoidal bunds) may take 50% more labour per unit volume of earthworks than smaller structures (e.g. Negarim microcatchments) because of increased earthmoving required. Typical rates per person/day range from 1.0 to 3.0 m<sup>3</sup>.
4. Labour rates for stoneworks: Typical labour rates achieved are 0.5 m<sup>3</sup> per person/day for construction. Transport of stone increases this figure considerably.

#### **Plate 5 Negarim microcatchment**



Although the first reports of such microcatchments are from southern Tunisia (Pacey and Cullis, 1986) the technique has been developed in the Negev desert of Israel. The word "Negarim" is derived from the Hebrew word for runoff - "Neger". Negarim microcatchments are the most well known form of all water harvesting systems.

Israel has the most widespread and best developed Negarim microcatchments, mostly located on research farms in the Negev Desert, where rainfall is as low as 100-150 mm per annum. However the technique, and variations of it, is widely used in other semi-arid and arid areas, especially in North and Sub-Saharan Africa Because it is a well-proven technique, it is often one of the first to be tested by new projects.

### **5.2.2 Technical details**

#### **i. Suitability**

Negarim microcatchments are mainly used for tree growing in arid and semi-arid areas.

Rainfall: can be as low as 150 mm per annum.

Soils: should be at least 1.5 m but preferably 2 m deep in order to ensure adequate root development and storage of the water harvested.

Slopes: from flat up to 5.0%.

Topography: need not be even - if uneven a block of microcatchments should be subdivided.

#### **ii. Overall configuration**

Each microcatchment consists of a catchment area and an infiltration pit (cultivated area). The shape of each unit is normally square, but the appearance from above is of a network of diamond shapes with infiltration pits in the lowest corners (Figure 17).

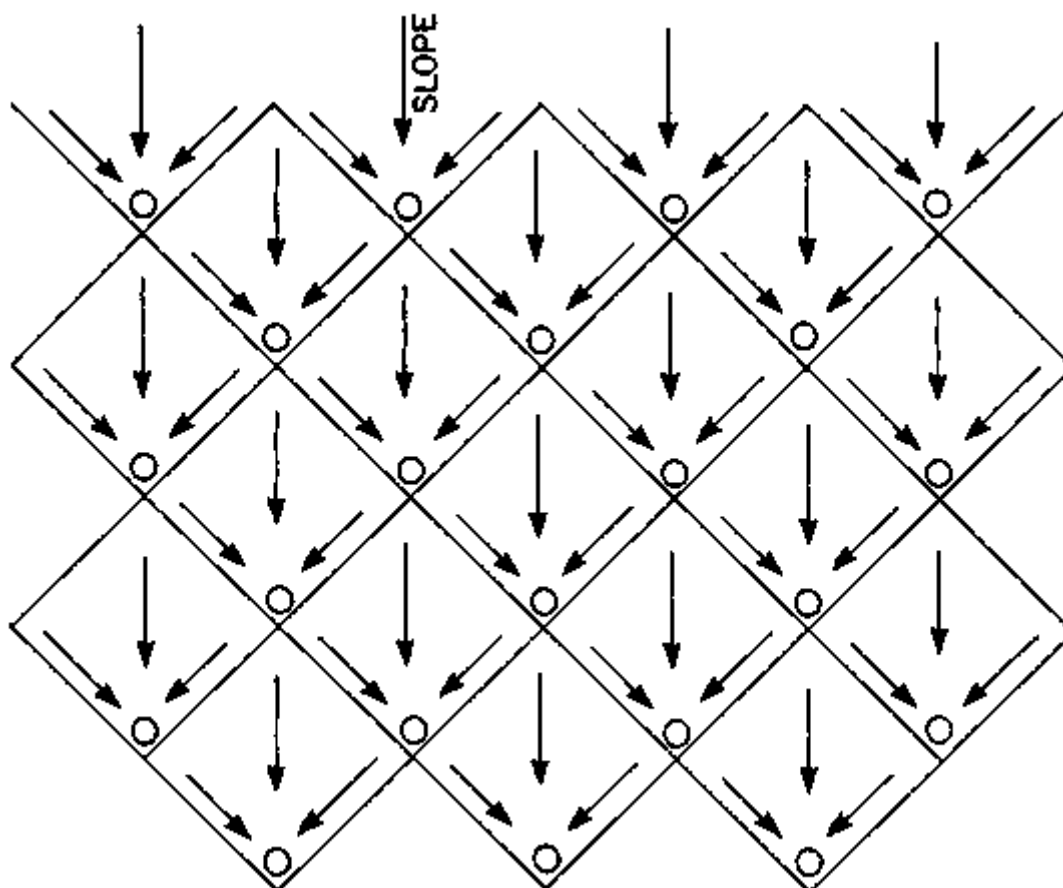
iii. Limitations

While Negarim microcatchments are well suited for hand construction, they cannot easily be mechanized. Once the trees are planted, it is not possible to operate and cultivate with machines between the tree lines.

iv. Microcatchment size

The area of each unit is either determined on the basis of a calculation of the plant (tree) water requirement (see Chapter 4) or, more usually, an estimate of this.

**Figure 17 Negarim microcatchments - field layout**



Size of microcatchments (per unit) normally range between 10 m<sup>2</sup> and 100 m<sup>2</sup> depending on the specie of tree to be planted but larger sizes are also feasible, particularly when more than one tree will be grown within one unit.

**Table 17. BUND HEIGHTS (cm) ON HIGHER GROUND SLOPES**

Size Unit Microcatchment	Ground slope
--------------------------	--------------

(m <sup>2</sup> )	2%	3%	4%	5%
3x3	even bund height			
4x4	of 25 cm			30
5X5			30	35
6X6			35	45
8X8		35	45	55
10X12	30	45	55	
12X12	35	50	not recommended	
15 X 15	45			

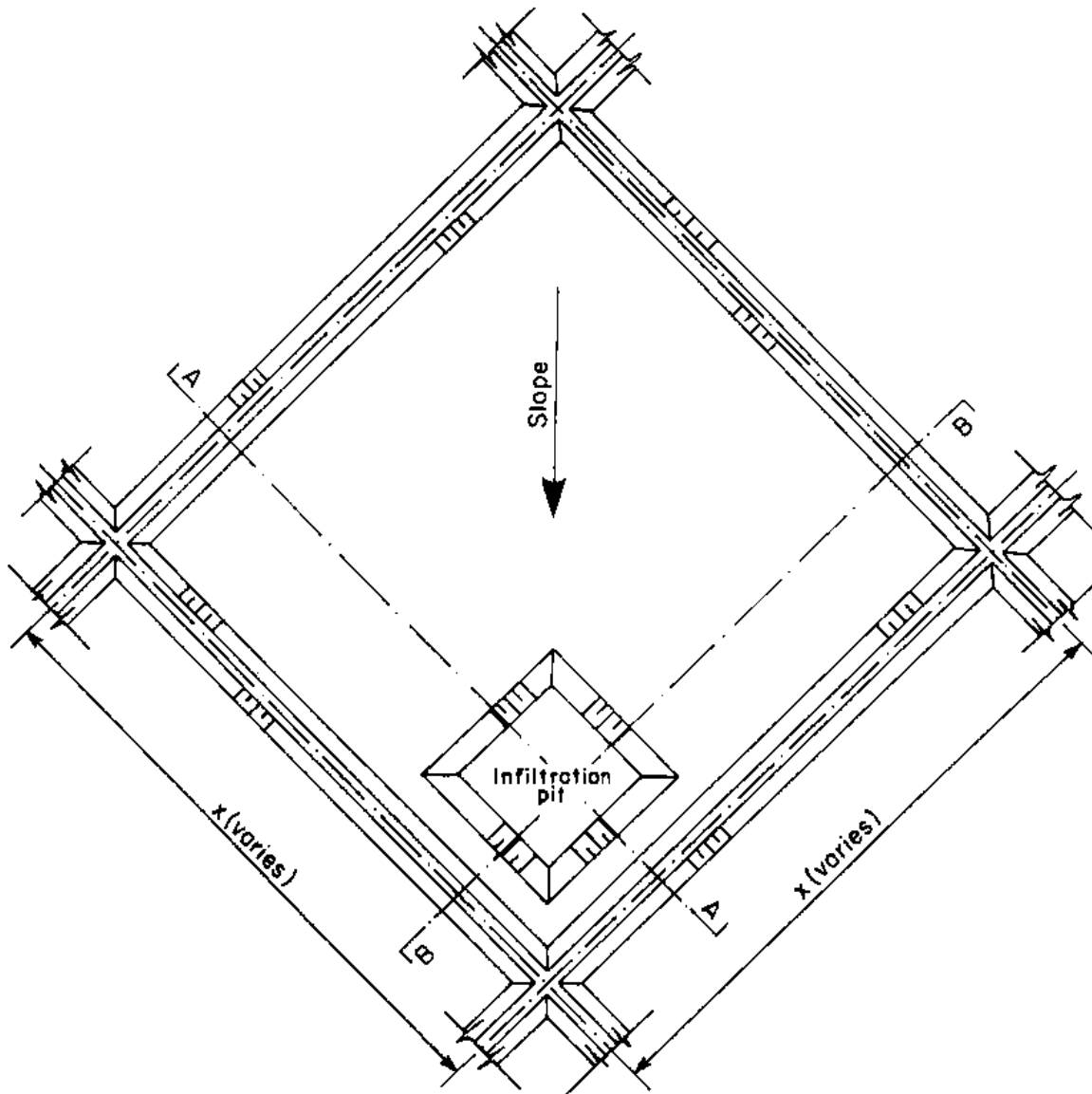
Note: These heights define the maximum height of the bund (below the pit).  
Excavation/total bund volume remain constant for a given microcatchment size.

#### v. Design of bunds

The bund height is primarily dependent on the prevailing ground slope and the selected size of the micro-catchment. It is recommended to construct bunds with a height of at least 25 cm in order to avoid the risk of over-topping and subsequent damage.

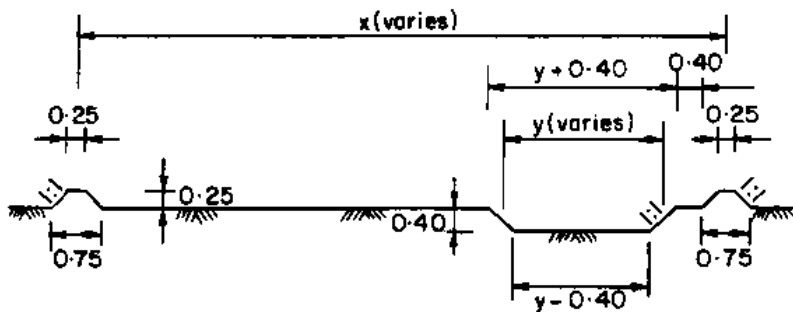
Where the ground slope exceeds 2.0%, the bund height near the infiltration pit must be increased. Table 17 gives recommended figures for different sizes and ground slopes.

**Figure 18. Negarim microcatchment: details for 0.25 m bund size (for dimensions x and y see Table 18)**



PLAN

(Planting step omitted for clarity)



SECTIONS. A-A, B-B

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 since this is the best protection against erosion.

vi. Size of infiltration pit

Table 18 presents recommended values for pit dimensions. A maximum 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.

vii. Quantities of Earthworks

Table 18 further gives required quantities of earthworks for different layouts. Quantities per unit include only the infiltration pit and two sides of the catchment, while the other two bunds are included in the microcatchment above. When a diversion ditch is required additional earthworks of 62.5 m<sup>3</sup> per 100 m length of ditch will be needed.

**Table 18. QUANTITIES OF EARTHWORKS FOR NEGARIM MICROCATCHMENTS**

(1)	(2)	(3)	(4)	(5)	(6) [
Size Unit Microcatchment (m <sup>2</sup> )	Size Infiltration Pit (m)	Ground Slopes Suitable for 25 cm Bund	Volume Earthwork Per Unit**	No. Units Per ha	Earthworks m <sup>3</sup> /ha
Sides (x) Area	Sides,(y) Depth	Height*	(m <sup>2</sup> )		
3 m x 3 m = 9 m <sup>2</sup>	1.4 x 1.4 x 0.4	up to 5%	0.75	1110	835
4 m x 4 m = 16 m <sup>2</sup>	1.6 x 1.6 x 0.4	up to 4%	1.00	625	625
5 m x 5 m = 25 m <sup>2</sup>	1.8 x 1.8 x 0.4	up to 3%	1.25	400	500
6 m x 6 m = 36 m <sup>2</sup>	1.9 x 1.9 x 0.4	up to 3%	1.50	275	415
8 m x 8 m = 64 m <sup>2</sup>	2.2 x 2.2 x 0.4	up to 2%	2.00	155	310
10 m x 10 m = 100 m <sup>2</sup>	2.5 x 2.5 x 0.4	up to 1%	2.50	100	250
12 m x 12 m = 144 m <sup>2</sup>	2.8 x 2.8 x 0.4	up to 1%	3.25	70	230
15 m x 15 m = 225 m <sup>2</sup>	3.0 x 3.0 x 0.4	up to 1%	3.50	45	160

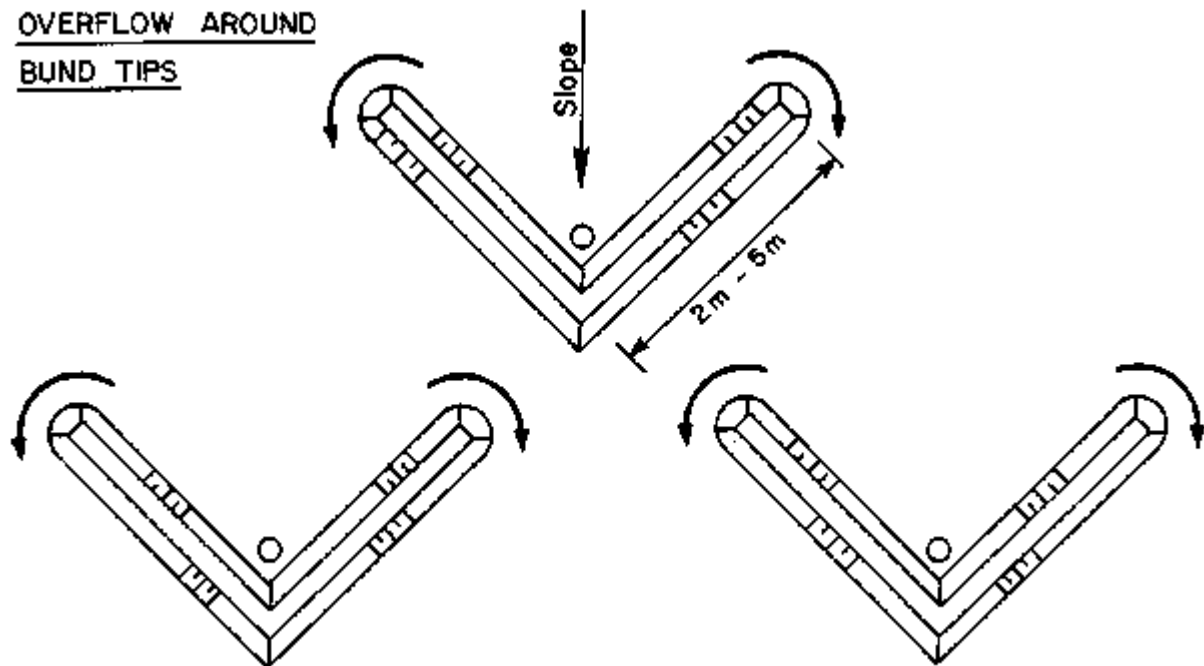
\* These ground slopes allow construction of a bund of 25 cm height throughout its length. Above these gradients the bund should be constructed relatively higher at the bottom (below the pit) and lower upslope. Table 17 gives the height of the bund below the pit for given microcatchment sizes.

\*\* Calculation of earthworks per unit includes only two of the sides around the catchment: the other two sides are included in the microcatchment above. Does not include earthworks required for diversion ditch (which is 62.5 m<sup>3</sup> for each 100 metre length).

### viii. Design Variations

A common variation is to build microcatchments as single, open-ended structures in "V" or semi-circular shape (see Figure 19). The advantage is that surplus water can flow around the tips of the bunds, however, the storage capacity is less than that of a closed system. These types of bunds are particularly useful on broken terrain, and for small numbers of trees around homesteads.

**Figure 19. "V"-shaped microcatchments**



### 5.2.3 Layout and construction

#### Step one

The first step is to find a contour line. This can be done by using a line level or a water tube level (see appendix). Since natural contours are often not smooth, it will be necessary to even out the contours so that finally a straight line is obtained. The first line, at the top of the block is marked (see Figure 20). If the topography is very uneven, separate smaller blocks of microcatchments should be considered.

#### Step Two

By means of a tape measure, the tips of the bunds are now marked along the "straightened contour". The first line will be open-ended. The distance between the tips (a-b) depends on the selected catchment size. Table 19 gives the corresponding distance between a-b for different catchment sizes.

**Table 19. DISTANCE BETWEEN BLINDS IN RELATION TO CATCHMENT SIZE**

Microcatchment dimension (m)	Distance a - b (m)
3x3	4.2
4x4	5.7
5x5	7.1
6x6	8.5
8x8	11.3
10x10	14.1

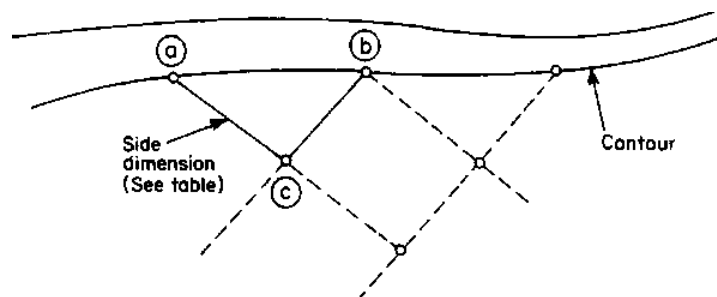
**Step Three**

A piece of string as long as the side length of the catchment (5 m for a 5 m x 5 m microcatchment) is held at one tip (a) and a second string of the same length at the other tip (b). They will exactly meet at the apex (c). The apex is now marked with a peg and the catchment sides (a-c) and (b-c) marked on the ground alongside the strings with a hoe. This procedure will be repeated until all bund alignments in the first row have been determined.

**Step Four**

The next row of microcatchments can now be staked out. The apexes of the bunds of the upper row will be the tips for the second row and the corresponding apexed will be found according to Step 3. When the second row of microcatchments has been marked, repeat the same procedure for the third row, etc. The final result will be a block of diamond-shaped microcatchments, with a first row which is open at the upslope end.

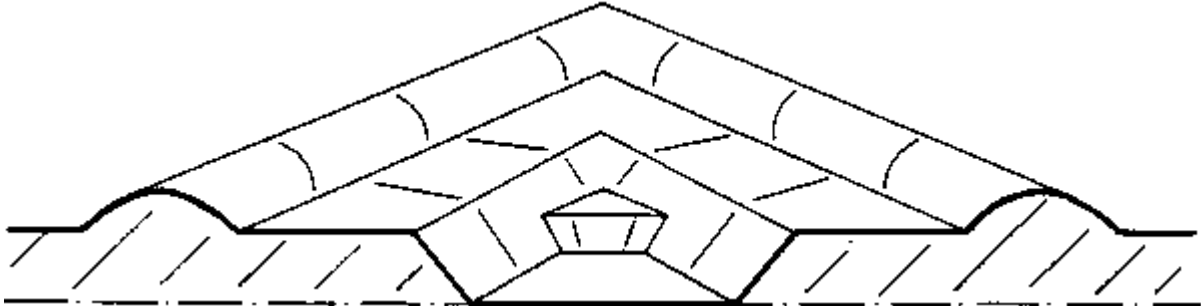
**Figure 20. Negarim microcatchment: layout technique**



**Step Five**

The size of the infiltration pit (dimension to be taken from Table 18) is staked out and the pit is excavated - leaving a small step towards the back on which the seedling will be planted (see Figure 21).

**Figure 21. Infiltration pit with planting step**



### Step Six

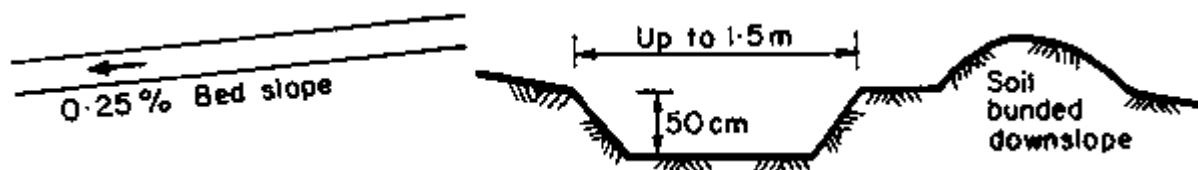
Before constructing the bunds, the area within the microcatchments should be cleared of all vegetation. The bunds should then be constructed in two layers. The excavated material from the pit is used to form the bund.

The bunds should be compacted during construction. Before compaction, the soil should be wetted wherever possible. Compaction may be done by foot or with a barrel filled with sand or water. To ensure a uniform height of the bund, a string should be fixed at the beginning and the end of each bund alignment and be adjusted above ground according to the selected bund height.

### Step Seven

A diversion ditch should be provided above the block of microcatchments if there is a risk of damage by runoff from upslope of the block. The diversion ditch should be aligned in a 0.25% slope and in most cases a depth of 50 cm and a width of 1.0-1.5 m will be sufficient. The soil is deposited downslope. The diversion ditch should be constructed first to prevent damage in case a rainstorm occurs during construction of the microcatchments.

**Figure 22. Diversion ditch**



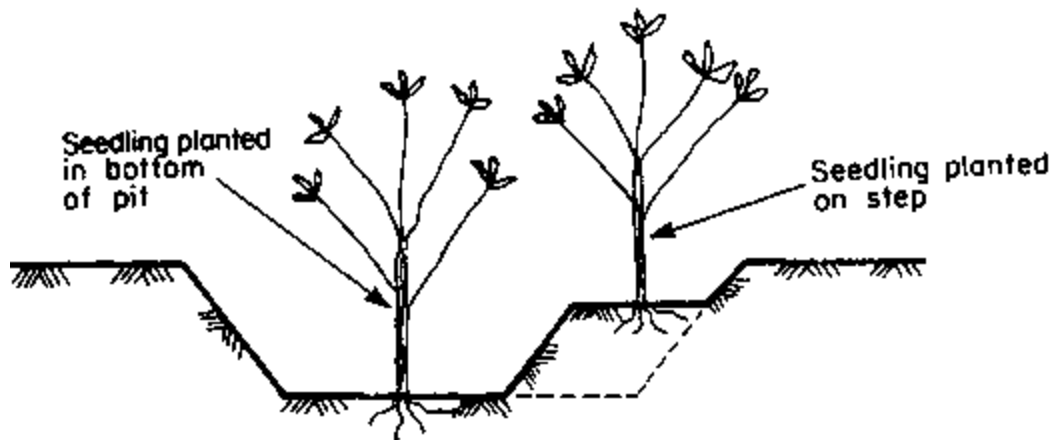
## 5.2.4 Maintenance

Maintenance will be required for repair of 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 if left unrepaired.

### 5.2.5 Husbandry

Tree seedlings of at least 30 cm height should be planted immediately after the first rain of the season. It is recommended that two seedlings are planted in each microcatchment - one in the bottom of the pit (which would survive even in a dry year) and one on a step at the back of the pit. If both plants survive, the weaker can be removed after the beginning of the second season. For some species, seeds can be planted directly. This eliminates the cost of a nursery.

Figure 23. Planting site for seedling



Manure or compost should be applied to the planting pit to improve fertility and water-holding capacity. If grasses and herbs are allowed to develop in the catchment area, the runoff will be reduced to some extent, however, the fodder obtained gives a rapid return to the investment in construction. Regular weeding is necessary in the vicinity of the planting pit.

### 5.2.6 Socio-economic considerations

Negarim microcatchments have been developed in Israel for the production of fruit trees, but even there the returns on investment are not always positive. It is not a cheap technique, bearing in mind that one person-day is required to build (on average) two units, and costs per unit rise considerably as the microcatchment size increases.

It is essential that the costs are balanced against the potential benefits. In the case of multipurpose trees in arid/semi-arid areas, for several years the main benefit will be the soil conservation effect and grass for fodder until the trees become productive.

Negarim microcatchments are appropriate both in village afforestation blocks, or around homesteads where a few open-ended "V" shaped microcatchments provide shade or support amenity trees.

#### PROFILE: Negarim Microcatchments in Rajasthan, India

Jujuba (*Ziziphus mauritiana*) is the best suited fruit tree for the arid areas of India. The plum-sized fruits are delicious and a rich source of vitamins.

The Central Arid Zone Research Institute (CAZRI) at Jodhpur, Rajasthan, has carried-out

experiments to investigate the effect of microcatchments on fruit production.

The findings were encouraging. Growth and fruit production were significantly improved by microcatchment techniques. On 0.5% slopes a 72 m catchment area per tree was sufficient to obtain excellent fruit yields. On a 5% slope the size could be reduced to 54 m<sup>2</sup> because of the increased runoff. Runoff coefficients increased over years due to a soil crust formed over the microcatchment surface.

Source: Sharma *et al.* (1986).

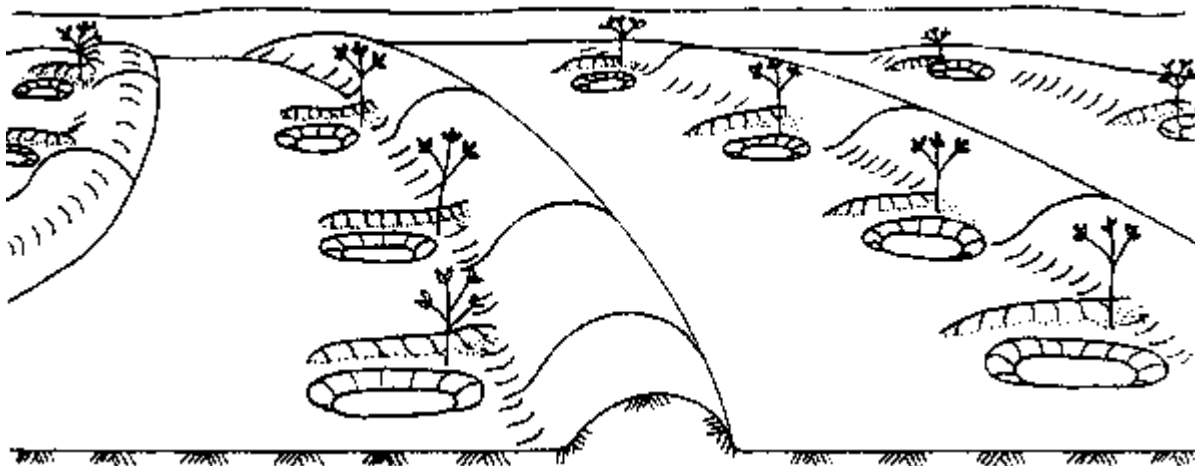
## 5.3 Contour bunds for trees

### 5.3.1 Background

Contour bunds for trees are a simplified form of microcatchments. Construction can be mechanized and the technique is therefore suitable for implementation on a larger scale. As its name indicates, the bunds follow the contour, at close spacing, and by provision of small earth ties the system is divided into individual microcatchments. Whether mechanized or not, this system is more economical than Negarim microcatchment, particularly for large scale implementation on even land - since less earth has to be moved. A second advantage of contour bunds is their suitability to the cultivation of crops or fodder between the bunds. As with other forms of microcatchment water harvesting techniques, the yield of runoff is high, and when designed correctly, there is no loss of runoff out of the system.

Contour bunding for tree planting is not yet as common as Negarim microcatchments. Examples of its application come from Baringo District, Kenya.

Figure 24 Contour bunds for trees



### 5.3.2 Technical details

#### i. Suitability

Contour bunds for tree planting can be used under the following conditions:

Rainfall: 200 - 750 mm; from semi-arid to arid areas.

Soils: Must be at least 1.5 m and preferably 2 m deep to ensure adequate root development and water storage.

Slopes: from flat up to 5.0%.

Topography: must be even, without gullies or rills.

## ii. Limitations

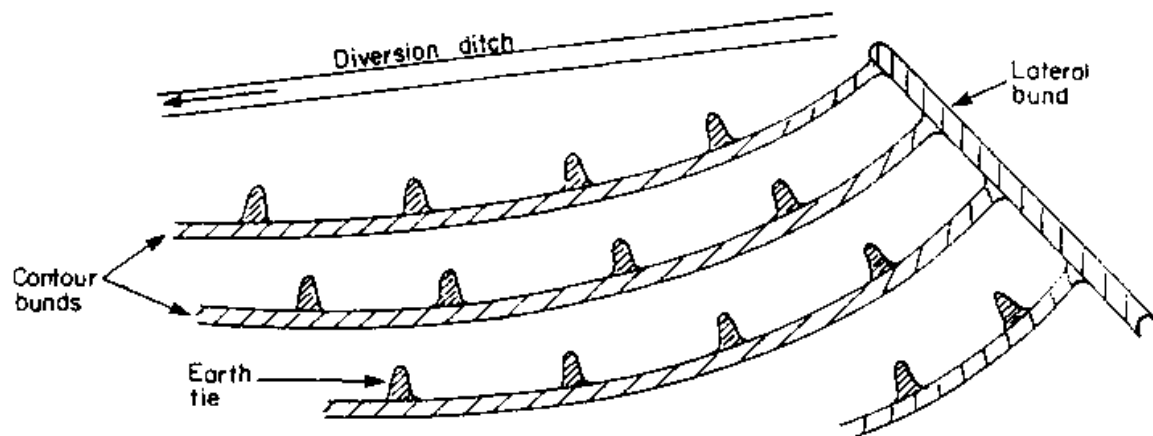
Contour bunds are not suitable for uneven or eroded land as overtopping of excess water with subsequent breakage may occur at low spots.

## iii. Overall Configuration

The overall layout consists of a series of parallel, or almost parallel, earth bunds approximately on the contour at a spacing of between 5 and 10 metres.

The bunds are formed with soil excavated from an adjacent parallel furrow on their upslope side. Small earth ties perpendicular to the bund on the upslope side subdivide the system into microcatchments. Infiltration pits are excavated in the junction between ties and bunds. A diversion ditch protects the system where necessary.

**Figure 25. Contour bunds for trees: field layout**



## iv. Unit Microcatchment Size

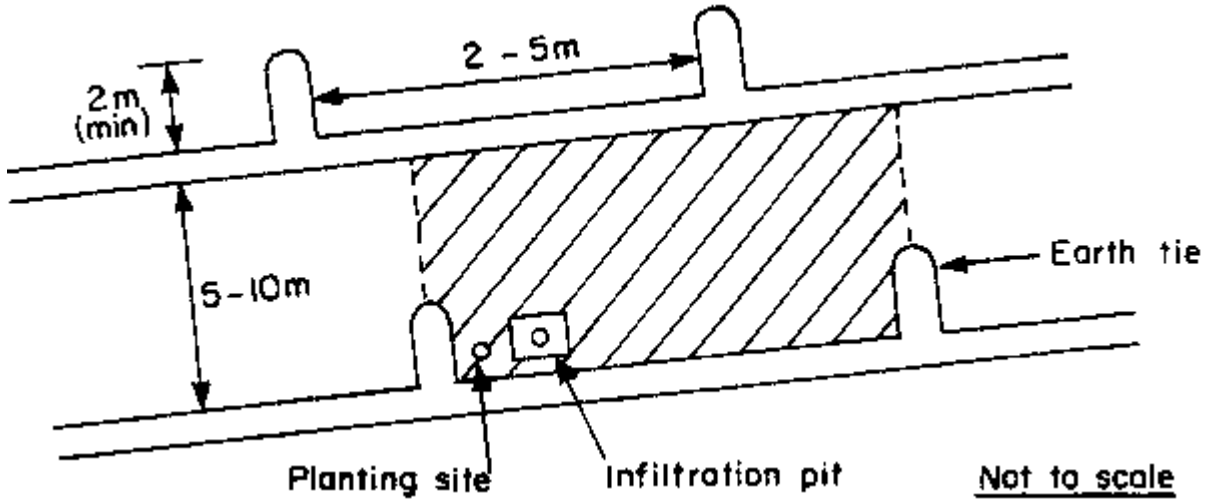
The size of microcatchment per tree is estimated in the same way as for Negarim microcatchments. However, the system is more flexible, because the microcatchment size can be easily altered by adding or removing cross-ties within the fixed spacing of the bunds. Common sizes of microcatchments are around 10 -50 m<sup>2</sup> for each tree.

## v. Bund and Infiltration Pit Design

Bund heights vary, but are in the order of 20 - 40 cm depending on the prevailing slope. As bunds are often made by machine the actual shape of the bund depends on the type of machine; whether for example a disc plough or a motor grader is used. It is recommended that the bund should not be less than 25 cm in height. Base width must

be at least 75 cm. The configuration of the furrow upslope of the bund depends on the method of construction.

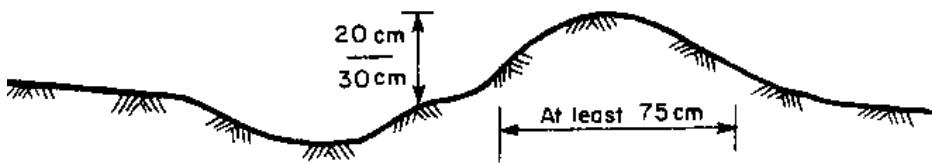
**Figure 26. Microcatchment unit**



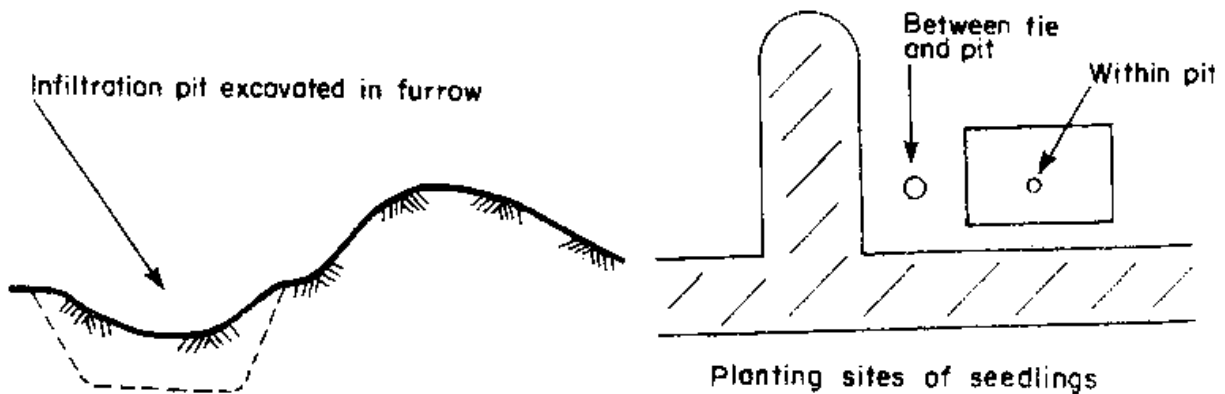
Bunds should be spaced at either 5 m or 10 m apart. Cross-ties should be at least 2 metres long at a spacing of 2 to 10 metres. The exact size of each microcatchment is thus defined. It is recommended to provide 10 m spacing between the bunds on slopes of up to 0.5% and 5 m on steeper slopes. A common size of microcatchment for multipurpose trees is 25 m<sup>2</sup>. This corresponds to 10 metre bund spacing with ties at 2.5 m spacing or 5 metre bund-spacing with ties at 5 m spacing.

Excavated soil from the infiltration pit is used to form the ties. The pit is excavated in the junction of the bund and the cross-tie. A pit size of 80 cm x 80 cm and 40 cm deep is usually sufficient.

**Figure 27. Bund dimensions**



**Figure 28. Infiltration pit and planting sites**



#### vi. Quantities of Earthwork

Table 20 gives quantities of earthworks required for various layouts of contour bunds. The bund height assumed is 25 cm with 75 cm base width.

**Table 20. QUANTITIES OF EARTHWORKS**

Size Unit Microcatchment			Volume Earthworks per Unit	No. Units per ha	Earthworks m <sup>3</sup> /ha
Bund spacing	Tie spacing	Area (m <sup>2</sup> )	(m <sup>3</sup> )		
5m	2m	10	0.5	1000	500
5m	5m	25	0.9	400	360
5m	10m	50	1.5	200	300
10m	2.5m	25	0.6	400	240
10m	5m	50	0.9	200	180

### 5.3.3 Layout and construction

#### Step One

The contour is determined by means of a simple surveying instrument, such as a line level or a water tube level (see appendix). As contour bunds are implemented on even land, contours need only be staked out approximately every 50 metres. The real contour should be smoothed to a gentle curve. Bunds may become slightly wider apart at one end to accommodate any change in the contour.

#### Step Two

The alignment of each bund should be marked on the ground before construction starts. As recommended under "bund design" the bunds should be set at a spacing of 10 m for slopes up to 0.5% and 5 m for steeper slopes. When disc ploughs are used, a single disc (with the remaining one or two removed) forms an adequate bund. Where available,

a reversible plough is preferred because furrows can be ploughed consecutively in both directions. Compaction of the bunds is recommended. When no machines are available, this should be done by foot or with a barrel filled with sand.

### **Step Three**

The catchment size required for each seedling determines the spacing between cross-ties. For example where a 25 m<sup>2</sup> catchment area is required and bunds are 10 metres apart the cross-ties will be 2.5 metres apart. Cross-ties are made by hand.

An infiltration pit of 80 cm x 80 cm and 40 cm deep is dug in the furrow above the bund. Water collected in the furrow will then drain into the pit and supply the adjacent seedling. The excavated material is sufficient to form a cross-tie of 2 m length, 75 cm base width and 25 cm height. The cross-tie extends upslope from the main bund at an angle of 90° to the main bund; at least 30 cm should be left between the cross-tie and the pit to allow sufficient space for planting the seedling.

### **Step Four**

At each side of the block, a lateral bund of 25 - 30 cm height is built to prevent loss of runoff out of the system. The earth should be excavated from inside the system and the contour bunds must be joined up with the lateral bund.

### **Step Five**

A diversion ditch should be provided above the scheme if there is a risk of damage by runoff from outside the block. The diversion ditch is aligned on a 0.25% slope and a common dimension is 50 cm deep and 1 - 1.5 m wide, with the soil piled downslope. The diversion ditch should be constructed before the contour bunds are built to prevent damage if rainstorms occur during construction.

## **5.3.4 Maintenance**

As with Negarim microcatchments, maintenance will in most cases be limited to repair of damage to bunds early in the first season. It is essential that any breaches -which are unlikely unless the scheme crosses existing rills - are repaired immediately and the repaired section compacted. Damage is frequently caused if animals invade the plots. Grass should be allowed to develop on the bunds, thus assisting consolidation with their roots.

## **5.3.5 Husbandry**

The majority of the husbandry factors noted under Negarim microcatchments also apply to this system: there are, however, certain differences.

Tree seedlings, of at least 30 cm height, should be planted immediately after the first runoff has been harvested. The seedlings are planted in the space between the infiltration pit and the cross-tie. It is advisable to plant an extra seedling in the bottom of the pit for the eventuality of a very dry year. Manure or compost can be added to the planting pit to improve fertility and water holding capacity.

One important advantage of contour bunds for tree establishment is that oxen or mechanized cultivation can take place between the bunds, allowing crops or fodder to be

produced before the trees become productive. However, this has the disadvantage of reducing the amount of runoff reaching the trees.

### 5.3.6 Socio-economic factors

Contour bunds for trees are mainly made by machine; costs of bund construction can be relatively low and implementation fast, especially where plots are large and even and the kind of mechanization well adapted.

However, as with all mechanization in areas with limited resources, there is a question mark about future sustainability. Experience has shown that very often the machines come abruptly to a halt when the project itself ends.

Another aspect that must be addressed is the management after the scheme has been established (which is usually done under the auspices of a development project). This is an issue which has to be seriously considered during the planning phase. Management of a large afforestation block by the local community is in most cases a new challenge and failure or success will depend on acceptance of the technique by the rural population.

#### **PROFILE: Contour Bunds for Trees in Baringo, Kenya**

The plains surrounding Lake Baringo in Kenya's semi-arid north are extensive but denuded of trees. Two major problems are observed here: the continuing erosion of the potentially fertile land by runoff and wind, and the increasing lack of fuelwood and fodder.

The Baringo "Fuel and Fodder Project" became operational in 1982 and developed the technique of contour bunding for tree planting using hired motor-graders for construction. 130 hectares, in blocks of about 10 ha in size and surrounded by solar-powered electric fences, were implemented up to 1987. Common species planted were **Acacia** spp., **Prosopis** spp., and **Combretum aculeatum**. While performance has not always been consistent, establishment and growth of the trees are generally good.

An interesting development is the growing importance attached by the people and the project authorities to the production of grass within the plots as a by-product. To avoid damage to the bunds, grazing is controlled. The grass is also used for thatching.

The management of the plot will be handed over to local village communities when procedures and guidelines have been worked out.

## 5.4 Semi-circular bunds

### 5.4.1 Background

Semi-circular bunds are earth embankments in the shape of a semi-circle with the tips of the bunds on the contour. Semi-circular bunds, of varying dimensions, are used mainly for rangeland rehabilitation or fodder production. This technique is also useful for growing trees and shrubs and, in some cases, has been used for growing crops. Depending on the location, and the chosen catchment: cultivated area ratio, it may be a short slope or long slope catchment technique. The examples described here are short slope catchment systems.

Semi-circular bunds, (the term "demi-lune" is used in Francophone Africa), are recommended as a quick and easy method of improving rangelands in semi-arid areas.

Semi-circular bunds are more efficient in terms of impounded area to bund volume than other equivalent structures - such as trapezoidal bunds for example. Surprisingly, this technique has never been used traditionally.

## 5.4.2 Technical details

### i. Suitability

Semi-circular bunds for rangeland improvement and fodder production can be used under the following conditions:

Rainfall: 200 - 750 mm: from arid to semi-arid areas.

Soils: all soils which are not too shallow or saline.

Slopes: below 2%, but with modified bund designs up to 5%.

Topography: even topography required, especially for design "a" (see below).

The main limitation of semi-circular bunds is that construction cannot easily be mechanized.

Since semi-circular bunds can be designed to a variety of dimensions, two specific designs are explained in this section. Design "a" comprises small structures, closely spaced. It is suitable for the relatively "wetter" semi-arid areas but requires low slopes and even terrain. Design "b", with larger and wider spaced bunds, is more suitable for drier areas, and does not need such even topography.

### ii. Overall configuration

The two designs of semi-circular bunds considered here differ in the size of structure and in field layout. Design "a" has bunds with radii of 6 metres, and design "b" has bunds with radii of 20 metres. In both designs the semi-circular bunds are constructed in staggered lines with runoff producing catchments between structures.

Design "a" is a short slope catchment technique, and is not designed to use runoff from outside the treated area, nor to accommodate overflow. Design "b" is also a short slope catchment system, but can accommodate limited runoff from an external source. Overflow occurs around the tips of the bund which are set on the contour.

### **Figure 29. Semi-circular bunds: field layout**



#### Design "a":

This design, suitable for slopes of 1% or less, consists of a series of small semi-circular bunds with radii of 6 metres. Each bund has a constant cross section over the whole length of 19 m. The recommended bund height is 25 cm with side slopes of 1:1 which result in a base width of 75 cm at a selected top width of 25 cm.

The tips of each bund are set on the contour, and 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.

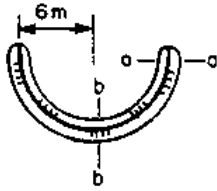
#### Design "b"

The radius of the semi-circle is 20 metres. The cross-section of the bund changes over its length. At the wing tip, the bund is only 10 cm high, but the height increases towards the middle of the base to 50 cm with side slopes of 3:1 (horizontal: vertical), and a top width of 10 cm. Corresponding base widths are 70 cm and 3.10 metres, respectively.

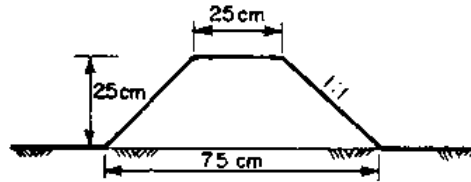
As with design "a", the bunds must be arranged in a staggered configuration. Due to the larger dimensions of the bunds there are only 4 structures required per hectare. The distance between the tips of two adjacent structures in one row is 10 m while 30 metres are recommended between the base of the upper structure and the tips of the lower one. As already mentioned above, radii and distances between the structures can be increased or decreased according to the selected C:CA ratio. Design "b" is recommended on slopes up to 2%. For higher slopes, smaller radii are required. For example, on a slope of 4%, the radius should be reduced to 10 metres and the distance between two adjacent rows from 30 metres to 15 metres while the tips of two adjacent structures should be 5 m apart instead of 10 m. The number of structures required for one hectare would thus increase to 16 which maintains the C:CA ratio of 3:1.

#### **Figure 30 Semi-circular bund dimensions**

**Design "a"**

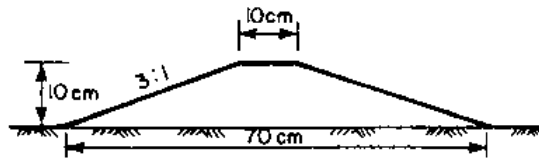
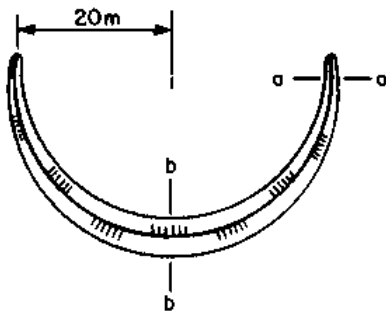


Not to scale

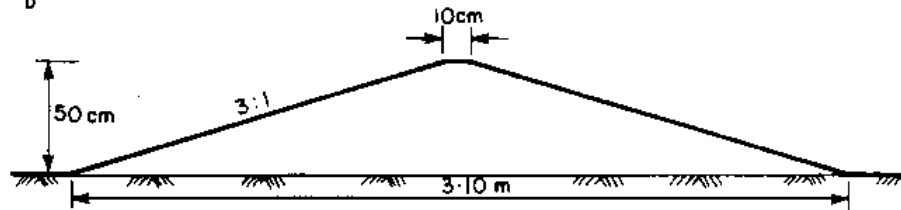


Cross Sections a-a, b-b

**Design "b"**



Section a-a



Section b-b

Not to scale

v. Quantities of earthworks

Table 21 gives quantities of earthworks required for different layouts.

It should be noted that where a diversion ditch is required (Design "a" only), 62.5 m<sup>3</sup> for each 100 metres of length has to be added to the figures in column 6.

**Table 21. QUANTITIES OF EARTHWORKS FOR SEMI-CIRCULAR BUNDS**

Land slope	Radius (m)	Length of bund (m)	Impounded area per bund (m <sup>2</sup> )	Earthworks per bund (m <sup>3</sup> )	Bunds per ha	Earthworks per ha (m <sup>3</sup> )
	(1)	(2)	(3)	(4)	(5)	(6)
Design "a" up to 1.0%	6	19	57	2.4	73	175
Design "b" up to	20	63	630	26.4	4	105

2.0%						
4.0%	10	31	160	13.2	16	210

vi. Design variations

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. A recommended radius for these smaller structures is 2 to 3 metres, with bunds of about 25 cm in height.

### 5.4.3 Layout, and construction

The layout for both designs is similar, only dimensions differ.

#### Step One

The first contour, at the top of the scheme, is staked out using a simple surveying instrument as described in the appendix. This line need not be smooth.

#### Step Two

A tape measure is now used to mark the tips of the semi-circular bunds on the contour. For design "a", the tips of one structure are 12 metres apart (2 times the radius) and the distance to the next unit is 3 m. For design "b", the tips are 40 metres apart and the distance to the next structure is 10 m.

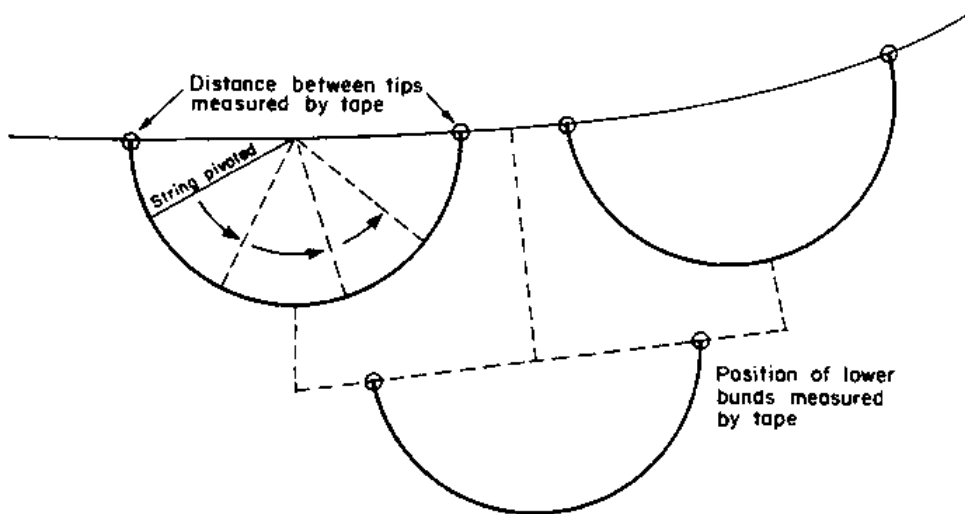
#### Step Three

The centre point between the tips of each semi-circular unit is marked. A piece of string as long as the selected radius is now fixed at the centre point by means of a peg. Holding the string tight at the other end, the alignment of the semi-circle is defined by swinging the end of the string from one tip to the other. The alignment can be marked by pegs or small stones (see Figure 31).

#### Step Four

Staking out and construction of the semi-circular bunds in the second and all following rows will be carried out in the same way. It is important that the structures in each row are staggered in relation to structures in the row above. The centre points of the bunds, for example, in the second row should coincide with the middle of the gaps between bunds in the first row and so forth. It must be ensured that the space between bunds from one row to another is according to the chosen distance, that is, 3 m for design "a" and 30 m for design "b".

#### Figure 31. Layout technique



### Step Five

After setting out, bund construction is started with excavation of a small trench inside the bund. Further excavation should always be from inside the bund, as evenly as possible. This will increase the storage capacity of the semi-circular bund. The bund should be constructed in layers of 10-15 cm with each layer being compacted and wetted first if possible.

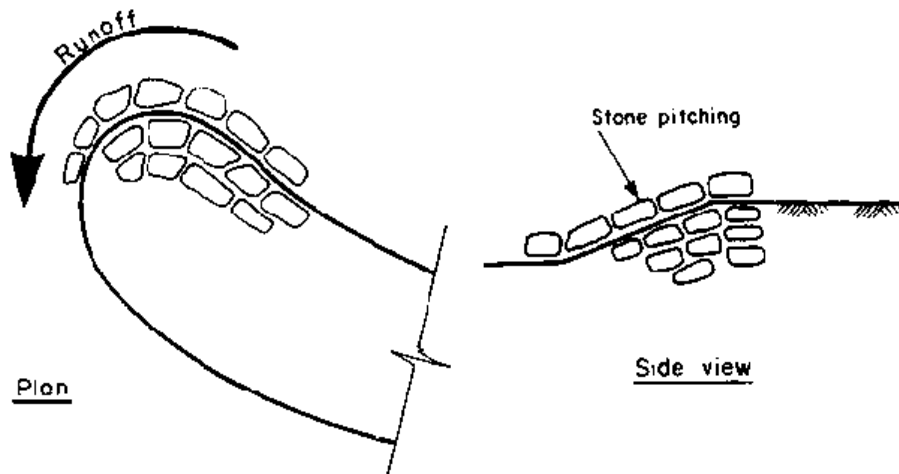
### Step Six

For design "b", it is recommended that the bund tips are protected with a layer of stones, as shown in Figure 32. This will ensure that the bund tips are more resistant to erosion when excess water discharges around them. A diversion ditch above the first row of structures may be necessary for design "a" to protect the first row of bunds against runoff coming from the catchment area above. Where semi-circular bunds of design "a" are built in one block of several hectares it is advisable to provide one or more diversion ditches within the block as a safety factor. Diversion ditches should be 1 - 1.5 metre wide and 50 cm deep, with a gradient of 0.25%.

### 5.4.4 Maintenance

As with all earthen structures, 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 fodder production 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. The situation is different if animals have access into the bunded area and are allowed to graze. In this case, regular inspections and maintenance (repair) of bund damages will be necessary.

**Figure 32. Protection of wingtips**



### 5.4.5 Husbandry

It may be possible to allow the already existing vegetation to develop - provided it consists of desirable species or perennial rootstocks. In most cases, however, it will be more appropriate to re-seed with seed from outside. Local collection of perennial grass seed from useful species can also be appropriate provided the seed is taken from "virgin land". Together with grass, trees and shrub seedlings may be planted within the bunds.

### 5.4.6 Socio-economic Factors

Water harvesting for range improvement and for fodder production will mainly be applied in areas where the majority of the inhabitants are agro-pastoralists - at least in the Sub-Saharan Africa context. In these areas, the concept of improving communally used rangeland is usually alien. Therefore, it may be difficult to motivate the population to invest voluntarily, in the time and effort required for implementing and maintaining such a water harvesting system. Even when this is possible it is equally important to introduce an appropriate and acceptable range management programme to avoid over-grazing and subsequent degradation of the range.

Controlled grazing is also essential to maintain good quality rangeland, and the banded area must be rested periodically for it to regenerate, so that natural reseeding can take place.

#### **PROFILE: "Demi-Lunes" in Tahoua Department, Niger**

Although semi-circular bunds are mostly used for growing grass, bushes or trees, the technique is also suitable for crop production. "Demi-lunes", literally "half moons", were introduced as a crop production technique by a Non-Government Organization in Tahoua Department of Niger during the mid-1980s. The concept was not only to concentrate runoff for crop production, but to rehabilitate degraded land in an area with an average annual rainfall of only 250- 300 mm.

The semi-circular bunds in this project are small, each with a radius of only about 2 metres. The total number within each block is about 300 per hectare, resulting in an average catchment: cultivated area ratio of 4:1. The "demi-lunes" were constructed by hand, using food-for-work rations during the construction time. The main crop grown is bulrush millet. In recent years the Government has tested a similar system for

rehabilitation of rangeland where, within the bunds, grass and trees were planted.

## 5.5 Contour ridges for crops

### 5.5.1 Background

Contour ridges, sometimes called contour furrows or microwatersheds, are used for crop production. This is again a microcatchment technique. Ridges follow the contour at a spacing of usually 1 to 2 metres. Runoff is collected from the uncultivated strip between ridges and stored in a furrow just above the ridges. Crops are planted on both sides of the furrow. The system is simple to construct - by hand or by machine - and can be even less labour intensive than the conventional tilling of a plot.

The yield of runoff from the very short catchment lengths is extremely efficient and when designed and constructed correctly there should be no loss of runoff out of the system. Another advantage is an even crop growth due to the fact that each plant has approximately the same contributing catchment area.

Contour ridges for crops are not yet a widespread technique. They are being tested for crop production on various projects in Africa.

#### Plate 6 Contour ridge system



### 5.5.2 Technical details

#### i. Suitability

Contour ridges for crop production can be used under the following conditions:

Rainfall: 350 - 750 mm.

Soils: all soils which are suitable for agriculture. Heavy and compacted soils may be a constraint to construction of ridges by hand.

Slopes: from flat up to 5.0%.

Topography: must be even - areas with rills or undulations should be avoided.

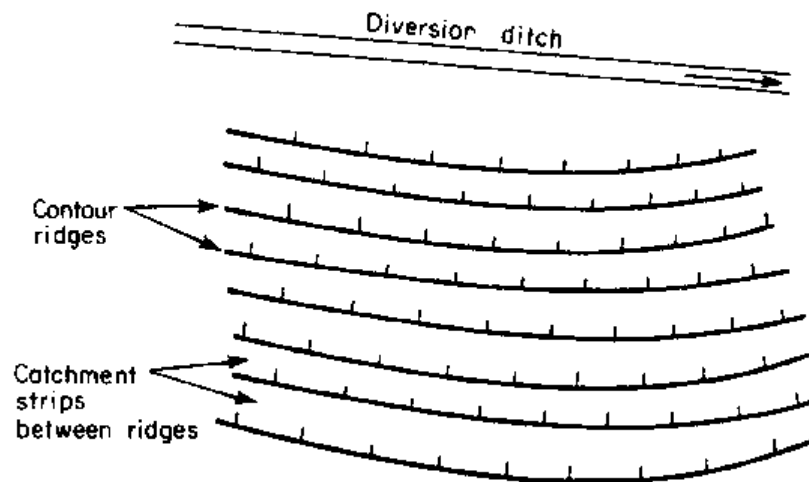
## ii. Limitations

Contour ridges are limited to areas with relatively high rainfall, as the amount of harvested runoff is comparatively small due to the small catchment area.

## iii. Overall configuration

The overall layout consists of parallel, or almost parallel, earth ridges approximately on the contour at a spacing of between one and two metres. Soil is excavated and placed downslope to form a ridge, and the excavated furrow above the ridge collects runoff from the catchment strip between ridges. Small earth ties in the furrow are provided every few metres to ensure an even storage of runoff. A diversion ditch may be necessary to protect the system against runoff from outside.

**Figure 33. Contour ridges: field layout**



## iv. Catchment: cultivated area ratio

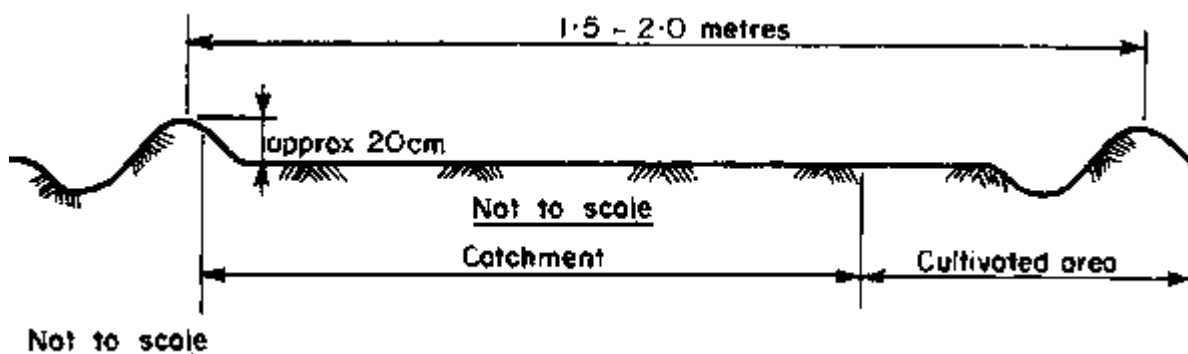
The cultivated area is not easy to define. It is a common practice to assume a 50 cm strip with the furrow at its centre. Crops are planted within this zone, and use the runoff concentrated in the furrow. Thus for a typical distance of 1.5 m between ridges, the C:CA ratio is 2:1; that is a catchment strip of one metre and a cultivated strip of half a metre. A distance of 2 metres between ridges would give a 3:1 ratio. The C:CA ratio can be adjusted by increasing or decreasing the distance between the ridges.

The calculation of the catchment: cultivated area ratio follows the design model of Chapter 4. In practice a spacing of 1.5 - 2.0 metres between ridges (C:CA ratios of 2:1 and 3:1 respectively) is generally recommended for annual crops in semi-arid areas.

## v. Ridge design

Ridges need only be as high as 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.

**Figure 34. Contour ridge dimensions**



**Table 22 QUANTITIES OF EARTHWORK FOR CONTOUR RIDGES**

Ridge spacing	Ridge & Tie height	Earthworks per ha
(m)	(cm)	(m <sup>3</sup> )
1.5	15	270
1.5	20	480
2.0	20	360

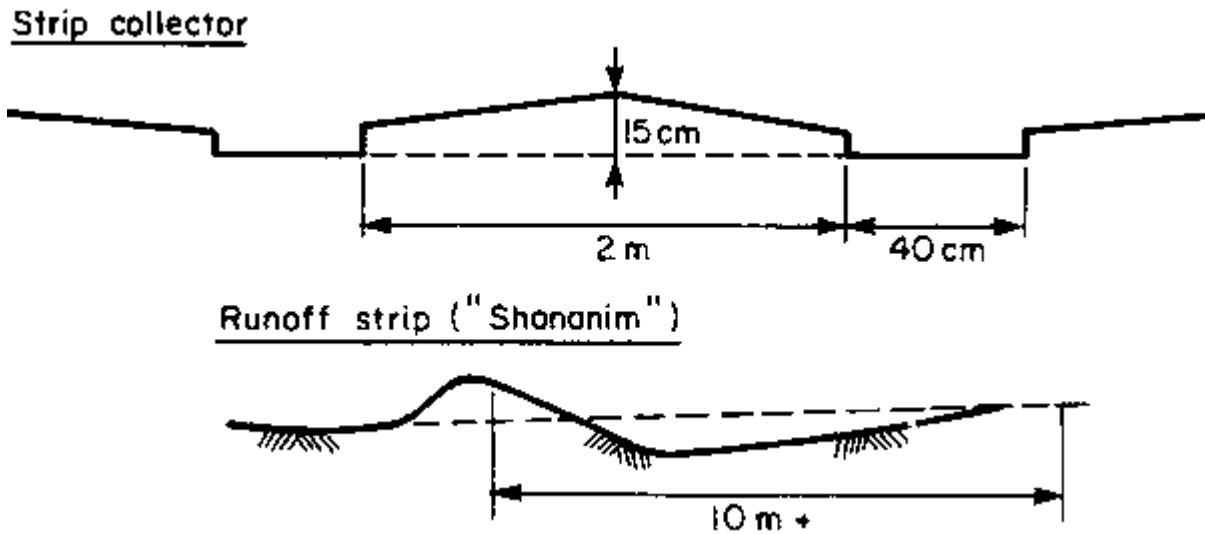
vi. Quantities and labour

Quantities of earthwork for different contour ridge spacing and ridge heights are given below. It should be noted that the construction of the ridges already includes land preparation - no further cultivation is required. Where a diversion ditch is necessary, an additional 62.5 m<sup>3</sup> for each 100 metre of length of ditch has to be added.

vii. Design variations

Design variations developed in Israel are the "runoff strips" ("Shananim") and "strip collectors" as described by Shanani and Tadmor (1979). A series of wide, but shallow ridges and furrows are formed by means of a blade grader. The space in between the ridges can be several metres (for strip collectors, the space is usually between 2-5 metres).

**Figure 35. Design variations**



### 5.5.3 Layout and construction

#### Step One

Contours are surveyed by a simple surveying instrument such as a water tube level or line level (see appendix). The real contour should be smoothed to obtain a better alignment for agricultural operations.

#### Step Two

Contour keylines should be staked out every 10 or 15 metres. The alignment for the ridges is then marked in between the keylines according to selected spacing. On uneven terrain, the contours may come closer together at one point or widen at other points. It is necessary to stop lines where the contours converge or to add short extra lines in between where the contours diverge.

#### Step Three

The furrows are excavated usually by means of a hoe or are ploughed parallel to the marked alignments for the ridges. The excavated soil is placed downslope, next to the furrow, and the ridge is formed.

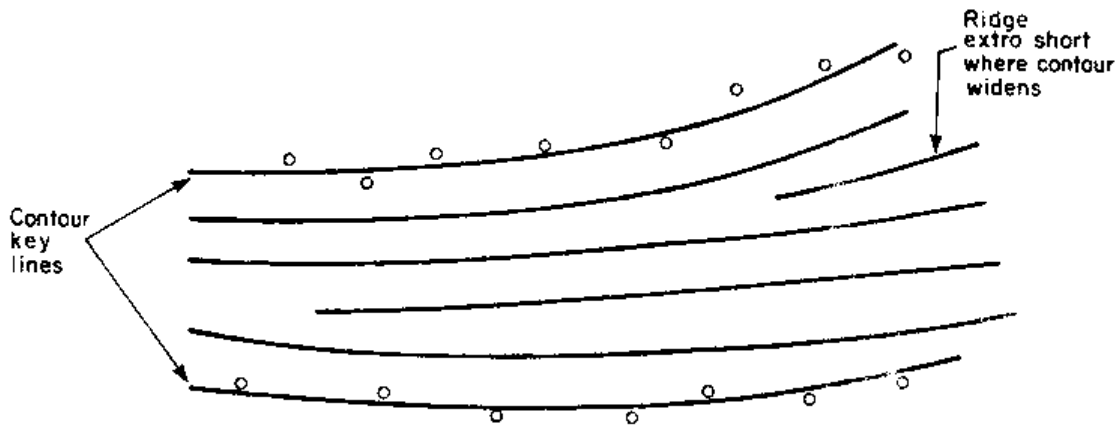
#### Step Four

Small cross-ties are built at intervals of about 5 metres dividing each furrow into a number of segments. The ties are 15-20 cm high and 50 - 75 cm long.

#### Step Five

A diversion ditch should be provided above the block of contour ridges if there is a risk of damage caused by runoff from outside the system. The diversion ditch should be 50 cm deep and 1-1.5 m wide, with a gradient of 0.25%. The excavated soil is placed downslope. The ditch should be constructed before the contour ridges are built to prevent damage from early rains.

**Figure 36. Contour ridges: layout technique**



### 5.5.4 Maintenance

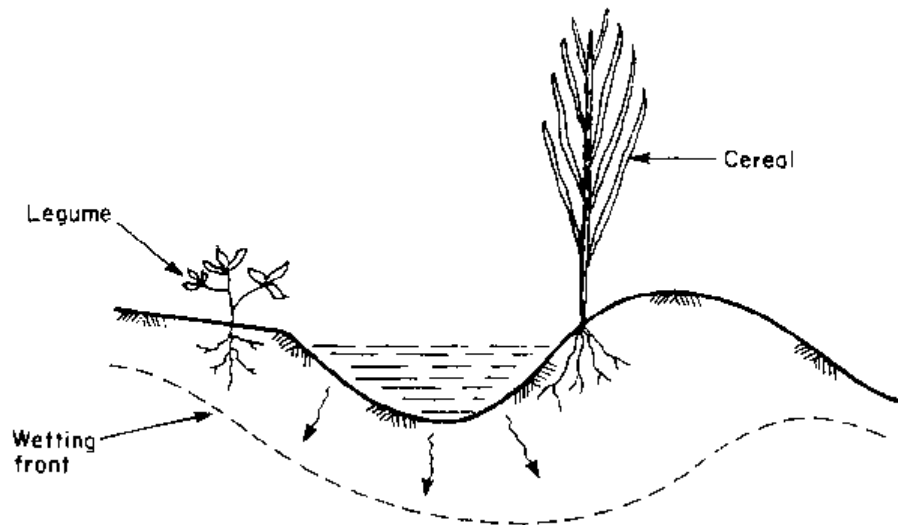
If contour ridges are correctly laid out and built, it is unlikely that there will be any overtopping and breaching. Nevertheless if breaches do occur, the ridges or ties must be repaired immediately. The uncultivated catchment area between the ridges should be kept free of vegetation to ensure that the optimum amount of runoff flows into the furrows.

At the end of each season the ridges need to be rebuilt to their original height. After two or three seasons, depending on the fertility status of the soils, it may be necessary to move the ridges downslope by approximately a metre or more, which will result in a fresh supply of nutrients to the plants.

### 5.5.5 Husbandry

The main crop (usually a cereal) is seeded into the upslope side of the ridge between the top of the ridge and the furrow. At this point, the plants have a greater depth of top soil. An intercrop, usually a legume, can be planted in front of the furrow. It is recommended that the plant population of the cereal crop be reduced to approximately 65% of the standard for conventional rainfed cultivation. The reduced number of plants thus have more moisture available in years of low rainfall.

**Figure 37. Planting configuration**



Weeding must be carried out regularly around the plants and within the catchment strip.

### 5.5.6 Socio-economic factors

Since the contour ridge technique implies a new tillage and planting method compared with conventional cultivation, farmers may be initially reluctant to accept this technique. Demonstration and motivation are therefore very important. On the other hand, it is one of the simplest and cheapest methods of water harvesting. It can be implemented by the farmer using a hoe, at no or little extra cost. External support is limited to a minimum. Alternatively it can be mechanized and a variety of implements can be used. When used by a farmer on his own land, the system does not create any conflicts of interest between the implementor and the beneficiary.

#### **PROFILE: Contour Ridges for Crops in Zinder Department, Niger**

While contour ridges can be made by hand or by animal draft, implementation can also be mechanized. This is particularly appropriate for larger scale implementation. The Integrated Programme for the Rehabilitation of Damergou, Niger is testing ways of bringing degraded land back into productive use, where annual rainfall is only in the range of 300 mm. The contour ridge technique for crop production was introduced 1988.

For this purpose, a special plough was designed to form the ridges, usually in straight lines (though approximately on the contour), at a distance of 2 metres apart. The machine is reversible, and the sub-soil beneath the furrows is ripped to increase infiltration rates. Cross ties are formed by the machine at an automatically controlled spacing. It is reported that one hectare can be treated in an hour, and up to 1,000 ha in a four month season by a single machine. The involvement of the villagers and implications for land tenure however need to be carefully taken into account as the programme develops.

## 5.6 Trapezoidal bunds

### 5.6.1 Background

Trapezoidal bunds are used to enclose larger areas (up to 1 ha) and to impound larger quantities of runoff which is harvested from an external or "long slope" catchment. The name is derived from the layout of the structure which has the form of a trapezoid -a base bund connected to two side bunds or wingwalls which extend upslope at an angle of usually 135°. Crops are planted within the enclosed area. Overflow discharges around the tips of the wingwalls.

The general layout, consisting of a base bund connected to wingwalls is a common traditional technique in parts of Africa. The concept is similar to the semi-circular bund technique: in this case, three sides of a plot are enclosed by bunds while the fourth (upslope) side is left open to allow runoff to enter the field. The simplicity of design and construction and the minimum maintenance required are the main advantages of this technique. This section is based on the design and layout of trapezoidal bunds implemented in Turkana District in northern Kenya.

### 5.6.2 Technical Details

#### i. Suitability

Trapezoidal bunds can be used for growing crops, trees and grass. Their most common application is for crop production under the following site conditions:

Rainfall: 250 mm - 500 mm; arid to semi-arid areas.

Soils: agricultural soils with good constructional properties i.e. significant (non-cracking) clay content.

Slopes: from 0.25% - 1.5%, but most suitable below 0.5%. Topography: area within bunds should be even.

#### ii. Limitations

This technique is limited to low ground slopes. Construction of trapezoidal bunds on slopes steeper than 1.5% is technically feasible, but involves prohibitively large quantities of earthwork.

#### iii. Overall configuration

Each unit of trapezoidal bunds consists of a base bund connected to two wingwalls which extend upslope at an angle of 135 degrees. The size of the enclosed area depends on the slope and can vary from 0.1 to 1 ha. Trapezoidal bunds may be constructed as single units, or in sets. When several trapezoidal bunds are built in a set, they are arranged in a staggered configuration; units in lower lines intersect overflow from the bunds above. A common distance between the tips of adjacent bunds within one row is 20 m with 30 m spacing between the tips of the lower row and the base bunds of the upper row (see Figure 38). The planner is of course free to select other layouts to best fit into the site conditions. The staggered configuration as shown in Figure 38 should always be followed. It is not recommended to build more than two rows



Slope:	1%
Crop water requirement:	475 mm per season
Design rainfall:	250 mm per season
Runoff coefficient:	0.25
Efficiency factor:	0.50

From Chapter 4:  $\frac{C}{CA} = \frac{475 - 250}{250 \times 0.5 \times 0.25} = \frac{225}{31.25} = 7.2$

But C = 20 ha

Thus  $CA = \frac{20}{7.2} = 2.8 \text{ ha}$

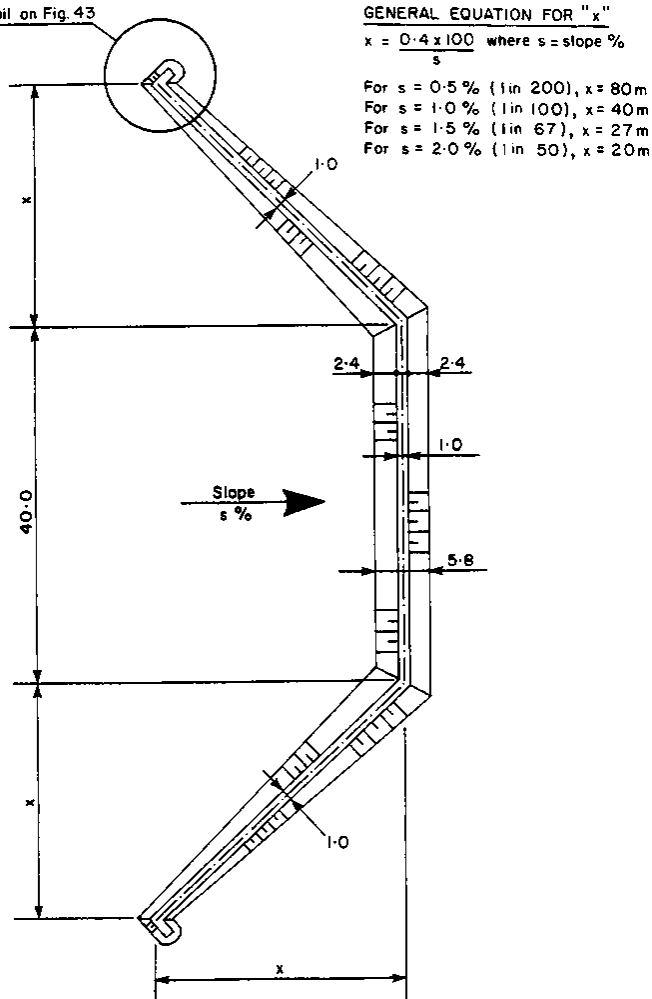
From Table 23 the area available for cultivation within one trapezoidal bund on a 1% slope is 3200 m<sup>2</sup> = 0.32 ha.

Therefore, number of bunds required:  $N = 2.8/0.32 = 8$

In common with all water harvesting techniques which rely on external catchments, the C:CA ratio is based on seasonal rainfall reliability in a year of relatively low rainfall. In years of high rainfall, and particularly under storm conditions resulting in excessive inflow, damage can be caused to crops and to the bunds themselves. This is particularly the case for bunds on steeper slopes and for those with high C:CA ratios. This results in recommendation of a maximum C:CA ratio of 10:1, although ratios of up to 30:1 are sometimes used. Where the use of a large catchment is unavoidable a temporary diversion ditch is advisable to prevent excessive inflow of runoff. Conversely, in situations where the catchment is not of adequate size, interception ditches can be excavated to lead runoff from adjacent catchments to the bunds.

**Figure 39. Trapezoidal bund dimensions**

See detail on Fig. 43



#### v. Bund design

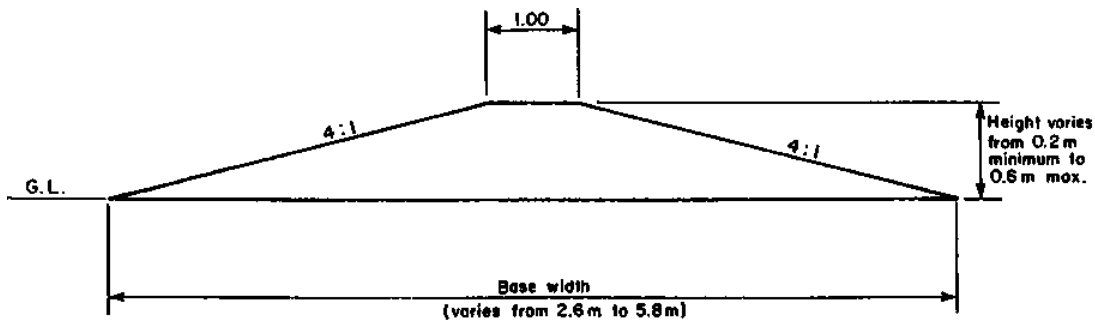
The criteria used in the design of bunds in Turkana were as follows:

Length of base bund:	40 m
Angle between base and side bunds:	135°
Maximum bund height:	0.60m
Minimum bund height (at tips):	0.20m

The configuration of the bunds is dependent upon the land slope, and is determined by the designed maximum flooded depth of 40 cm at the base bund. Consequently as the gradient becomes steeper the wingwalls extend less far upslope as is illustrated in Figure 39. The greater the slope above 0.5%, the less efficient the model becomes because of increasing earthwork requirements per cultivated hectare (see Table 23).

Bund cross-sections are shown in Figure 40 and are based on a 1 metre crest width and 4:1 (horizontal: vertical) side slopes.

Figure 40. Trapezoidal bund: standard cross-section



vi. Dimensions and quantities of earthworks

Table 23 gives details of dimensions and earthworks quantities in the Turkana model for different slopes. Earthworks are also quoted per hectare of cultivated area.

vii. Design variations

The configurations and design criteria outlined above apply to bunds installed in the Turkana District of Kenya. Considerable variations are possible dependent on climatic, physical and socio-economic conditions. The optimum design for an individual set of circumstances can only be achieved by a process of trial and error.

Figure 41. "Teras" system, Eastern Sudan (Source: Critchley and Reij 1989)

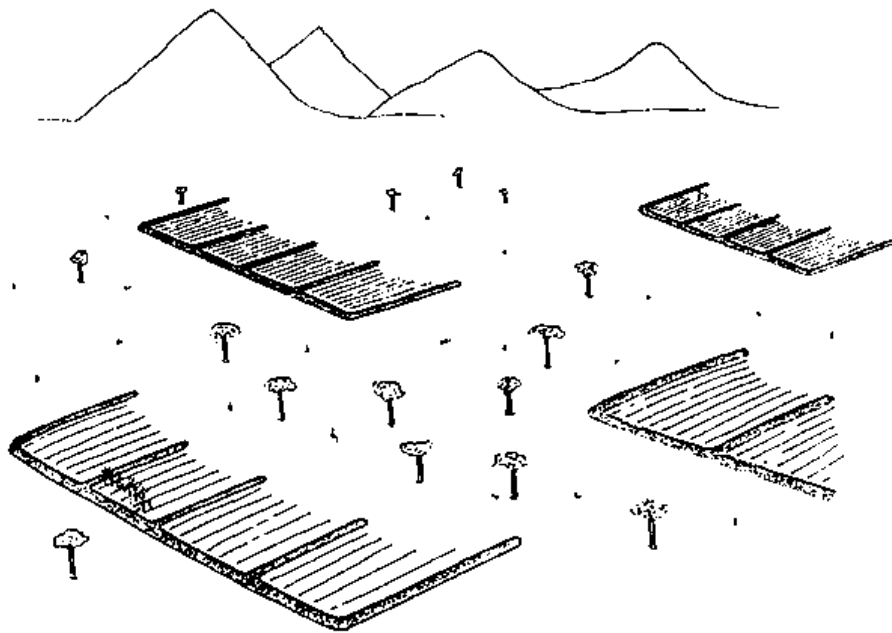


Table 23. QUANTITIES OF EARTHWORKS FOR TRAPEZOIDAL BUND

Slope(%)	Length of base bund (m)	Length of wingwall (m)	Distance between tips (m)	Earthworks per bund (m <sup>3</sup> )	Cultivated area per bund (m <sup>2</sup> )	Earthworks per ha cultivated (m <sup>3</sup> )
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0.5	40	114	200	355	9600	370
1.0	40	57	120	220	3200	670
1.5	40	38	94	175	1800	970

Note: Where diversion ditches or collection arms are required these add 62.5 m<sup>3</sup> for each 100 m length.

Traditional forms of water harvesting, similar to trapezoidal bunds, are found in the clay plains of Eastern Sudan and also in Somalia. In Sudan, the layout of the bunds is rectangular with the wingwalls extending upslope at right angles to the base bund. In Northwest Somalia a development project has constructed banana-shaped bunds by bulldozer.

### 5.6.3 Layout and construction

#### Step One

When the site for the bund has been decided, the first thing to do is to establish the land slope using an Abney level or line level as described in the Appendix. Dimensions for bunds on different slopes are given in Table 23. Having established the ground slope, the tips of the wingwalls will be determined.

Starting at the top of the field a peg is placed which will be the tip of one of the wingwalls (point 1). The second wingwall tip (point 2) is at the same ground level at the distance obtained from Table 23. This is set out using a line level and a tape as described in the Appendix and is marked by a peg.

#### Step Two

The dimensions for staking out the four main points of the bund are shown on Figure 42. Point "a" can be established by measuring the distance "x" from Point 1 along the line joining points 1 and 2. Values for "x" (for different slopes) can be obtained from Figure 39. Similarly, Point "b" is established by measuring the distance "x" from Point 2 along the line joining points 1 and 2. Points 3 and 4, which are the points of intersection of the base bund and the wingwalls, lie a distance x downslope from points "a" and "b" respectively, measured at right angles to the line joining Point 1 and Point 2. The right angle can most easily be found by using a wooden right angle triangular template (sides: 100 cm, 60 cm and 80 cm). Points 3 and 4 are then pegged.

#### Step Three

The accuracy of the setting out can be checked by measuring the distances between Point 3 and Point 4, Point 3 and Point 1, and Point 2 and Point 4 which should be:

Point 3 - Point 4 = 40 m

Point 1 - Point 3 = Point 2 - Point 4

**Figure 42. Trapezoidal bund: staking out of main points**

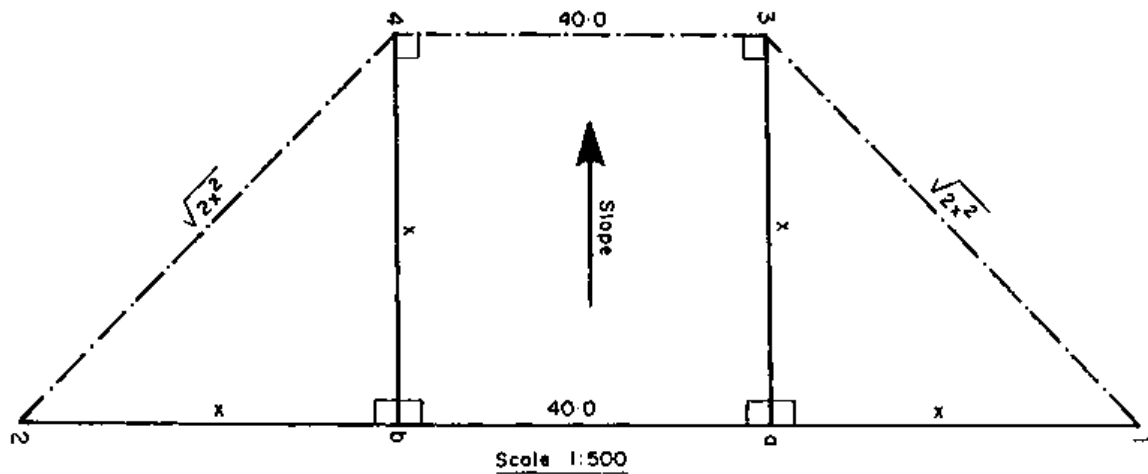
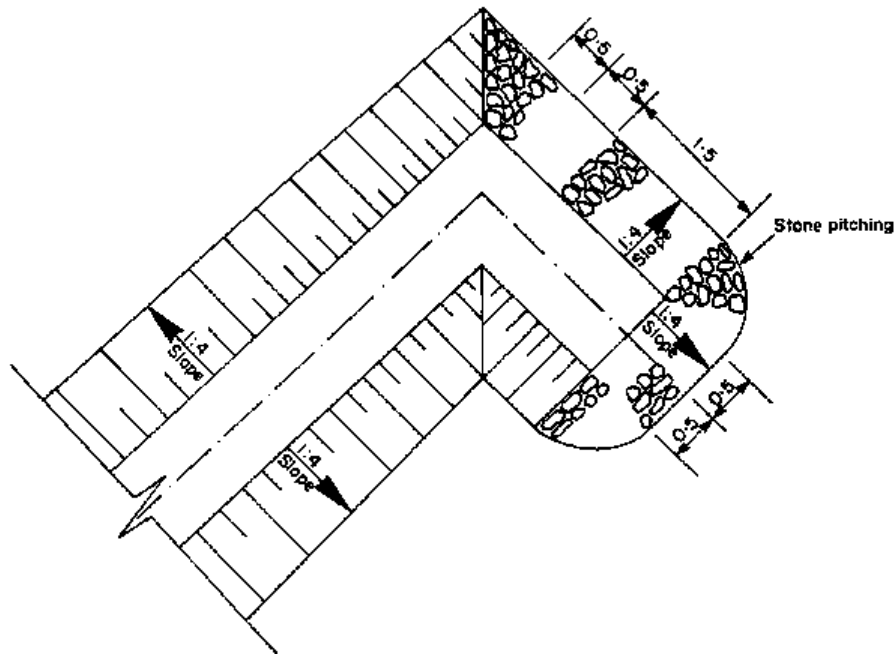


Figure 43. Trapezoidal bund: detail of tip



If, on checking, there is an error greater than 0.5 m in any of these three dimensions, the setting out procedure should be repeated.

#### Step Four

Having set the main points of the bunds it is necessary then to set out pegs or stones to mark the earthworks limits. Along the base bund this is done by marking parallel lines at a distance of 2.9 m from Line 3-4. For the wingbunds, the demarcation of the earthworks limits is slightly more complicated. At point 1 (2) perpendicular distances of 1.30 m either side of the wingbund centreline are measured and marked. At point 3 (4) distances of 2.90 m either side and perpendicular to the wingbunds centreline (line 1-3, 2-4) are measured and marked. It is then possible to peg out earthwork limits on both sides of the wingbunds centreline. Where more than one bund is required, the other bunds should be pegged out accordingly.

### **Step Five**

Construction of a set of trapezoidal bunds must start with the row furthest upslope. Before commencing construction the soil within the foundation area of the bunds should be loosened to ensure good "mating" with the fill. The bund is constructed in two layers, each having a maximum thickness of 0.30 m. The thickness of the first layer will gradually taper off to zero as filling proceeds upslope along the wingbunds. Similarly, the thickness of the second layer will taper to 0.20 m at the tips. Each layer should be thoroughly compacted by rolling, ramming or stamping, and should be watered prior to compaction, where this is possible.

Excavation to provide the necessary fill should be taken from within the banded area, where possible, to assist in levelling the area within the bund to promote even depth of flooding. Material for fill should not be excavated adjacent to the bunds on their downslope side, as this promotes gullying and bund failure.

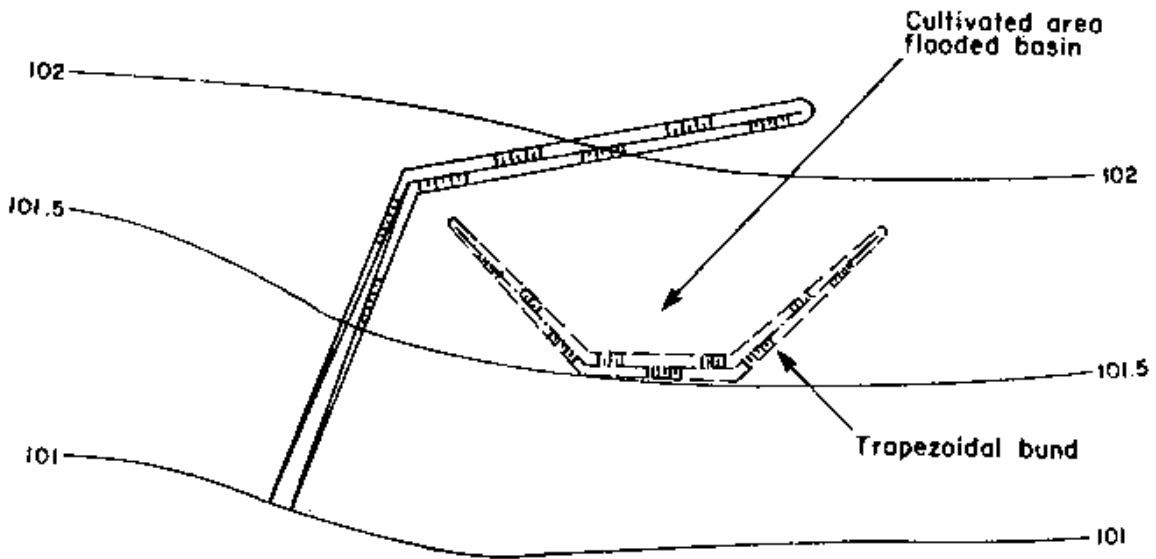
### **Step Six**

The tips of the bunds are only 20 cm high, and excess runoff drains around them. To prevent erosion of the tips they should be shaped with a small extension or "lip" to lead water away. This lip should be pitched with stones for extra resistance to erosion. Suggested dimensions are shown in Figure 43.

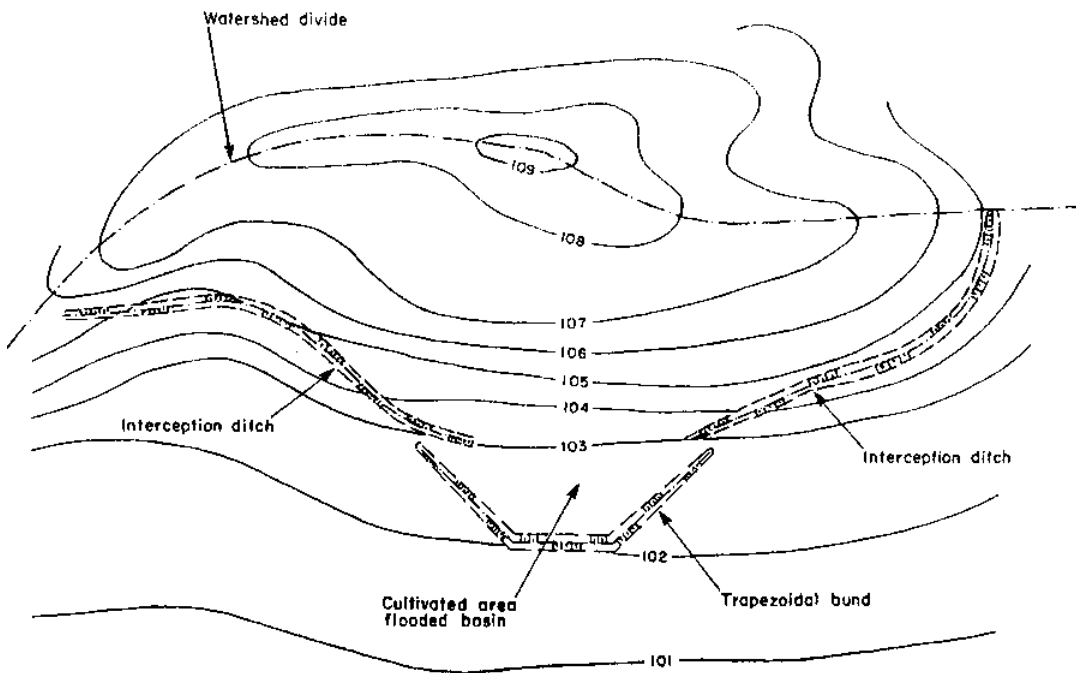
### **Step Seven**

Where the catchment is large in relation to the banded area, it is advisable to construct a diversion ditch to prevent excessive inflow to the bunds. This ditch is usually 50 cm deep and of 1.0 to 1.5 metres width, and is usually graded at 0.25%. Soil excavated from the ditch is used to construct an embankment on the downslope side, which also assists in diverting runoff from the bunds. During the early part of the season breaches can be made in this embankment at approximately 10 metre intervals and the material used to temporarily plug the ditch, thus permitting runoff to enter the trapezoidal bunds. As shown on Figure 44, it is necessary to continue excavation of the ditch some distance downslope, to allow its bed level to reach ground level. Over this length the bed width of the ditch should be gradually increased to 3 metres.

### **Figure 44. Trapezoidal bund: diversion ditch**



**Figure 45. Interception ditch**



### Step Eight

In situations where the catchment is not of adequate size, interception ditches can be made to lead runoff from adjacent catchments to the bunds. These are opposite in effect to diversion ditches but have similar sizes and design criteria. An example is shown in Figure 45.

### 5.6.4 Maintenance

If there are breaches in the bund, these must be repaired immediately, and the earth compacted thoroughly. Breaches are often caused by poor construction, or because the

catchment area is producing damaging amounts of runoff - or both. It is advisable to construct a diversion ditch to protect the repaired bund.

Holes burrowed by rodents can be another cause of breaching. These should be filled in whenever spotted. Allowing natural vegetation to grow on the bunds leads to improved consolidation by the plant roots. Repairs to the wing tips will frequently be needed when overflow has occurred. These should be built up, and extra stone pitching provided if required.

### 5.6.5 Husbandry

Trapezoidal bunds are normally used for production of annual crops in dry areas. The most common crops are cereals, and of these sorghum and bulrush (pearl) millet are by far the most usual. Sorghum is particularly appropriate for such systems because it is both drought tolerant and withstands temporary waterlogging. In the trapezoidal bund, water tends to be unevenly distributed because of the slope, and ponding often occurs near the base bund. Likewise the upper part may be relatively dry. Sorghum can tolerate both these situations.

Planting is carried out in the normal way, after ordinary cultivation of the soil within the bund. It is usual to plough parallel to the base bund, so that the small furrows formed by ploughing will locally accumulate some water. In the driest areas planting is sometimes delayed until a runoff event has saturated the soil within the bund, and germination/establishment is guaranteed. It is also possible to make use of out-of-season showers by planting a quick maturing legume, such as cowpea or tepary beans (**Phaseolus acutifolius**). Another useful technique is to plant cucurbits like gourds or watermelons on the bottom bund if water ponds deeply.

### 5.6.6 Socio-economic factors

It is difficult to generalize about the socio-economic factors concerning trapezoidal bunds, as different variations are found in different circumstances. As mentioned previously, there are examples of similar structures being used traditionally in Sudan - where they are often made by hand, without assistance from any agency and evidently perform well. On the other hand trapezoidal or similar bunds have been installed in other places under projects using food-for-work labour or even heavy machinery. When this has been done without any significant beneficiary commitment the bunds have been quickly abandoned. The amount of earthmoving necessary for trapezoidal bunds means that their construction usually requires organized labour or machinery and is beyond the scope of the individual farmer. However, where adequate motivation exists, there is considerable scope for the technique which has a traditional basis and does not require new farming skills.

#### **PROFILE: Trapezoidal Bunds in Turkana District, Kenya**

Trapezoidal bunds were designed for Turkana District when a widespread food relief operation was underway in 1984. A policy of food-for-work had followed the free distribution of food at the beginning of the crisis. The first attempts at water harvesting, based on contour bunds, were not well designed or supervised. The result was extensive bunding which was not useful - and not used. The design for trapezoidal bunds was based on scientific principles and the best available data on rainfall and runoff. There was a deliberate policy to "over-design" as food-rewarded labour was not limiting and it was

desired to make the structures as maintenance free as possible. By 1987 about 150 trapezoidal bunds had been constructed for the production of quick maturing food crops including sorghum and cowpeas. The Turkana Water Harvesting Project, a small NGO in the northeast of the District, has modified the basic design for local conditions. Although the line level is used for setting out the bunds, catchment sizes are estimated by eye and the experience of locally trained technicians.

## 5.7 Contour stone bunds

### 5.7.1 Background

Contour stone bunds are used to slow down and filter runoff, thereby increasing infiltration and capturing sediment. The water and sediment harvested lead directly to improved crop performance. This technique is well suited to small scale application on farmer's fields and, given an adequate supply of stones, can be implemented quickly and cheaply.

Making bunds - or merely lines - of stones is a traditional practice in parts of Sahelian West Africa, notably in Burkina Faso. Improved construction and alignment along the contour makes the technique considerably more effective. The great advantage of systems based on stone is that there is no need for spillways, where potentially damaging flows are concentrated. The filtering effect of the semi-permeable barrier along its full length gives a better spread of runoff than earth bunds are able to do. Furthermore, stone bunds require much less maintenance.

Stone bunding techniques for water harvesting (as opposed to stone bunding for hillside terracing, a much more widespread technique) is best developed in Yatenga Province of Burkina Faso. It has proved an effective technique, which is popular and quickly mastered by villagers.

#### Plate 8 Contour stone bund



## 5.7.2 Technical details

### i. Suitability

Stone bunds for crop production can be used under the following conditions:

Rainfall: 200 mm - 750 mm; from arid to semi-arid areas.

Soils: agricultural soils.

Slopes: preferably below 2%.

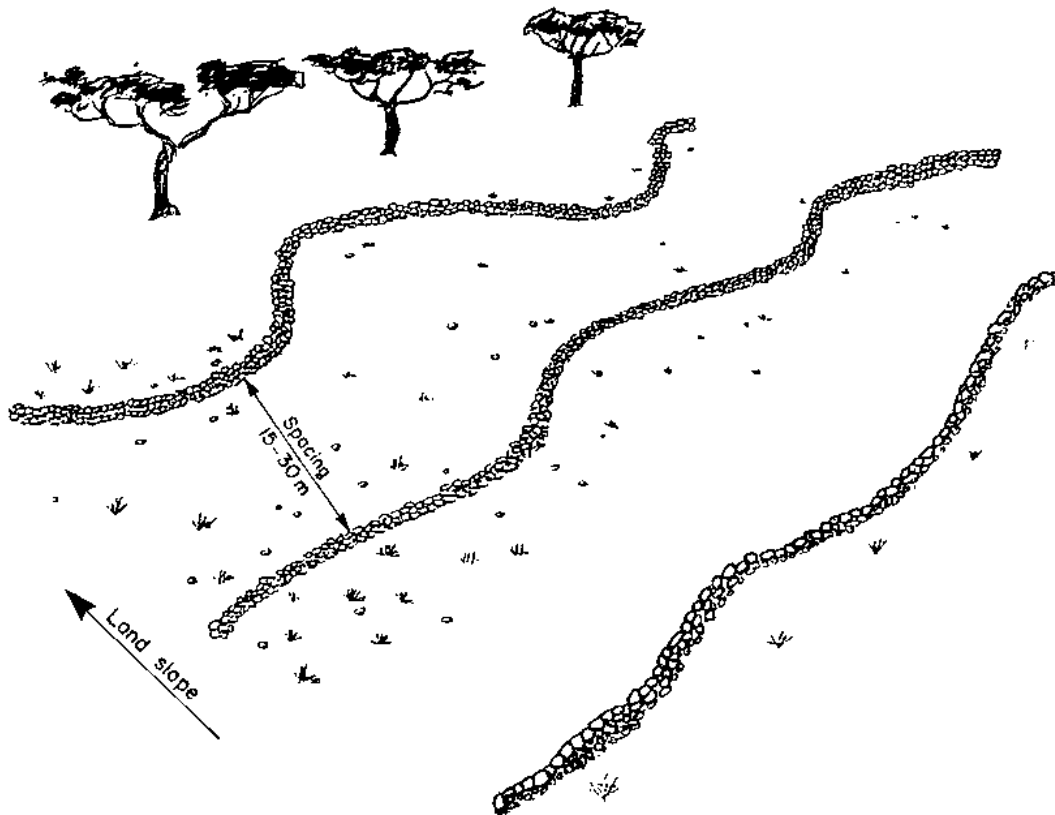
Topography: need not be completely even.

Stone availability: must be good local supply of stone.

### ii. Overall configuration

Stone bunds follow the contour, or the approximate contour, across fields or grazing land. The spacing between bunds ranges normally between 15 and 30 m depending largely on the amount of stone and labour available. There is no need for diversion ditches or provision of spillways.

**Figure 46. Contour stone bunds: field layout (Source: Critchley and Reij 1989)**



**Table 24. QUANTITIES AND LABOUR REQUIREMENTS FOR CONTOUR STONE BUNDS**

	Bund size	Bund spacing = 15 m		Bund spacing = 20 m	
		Vol. stone m <sup>3</sup> /ha	Person days/ha	Vol. stone m <sup>3</sup> /ha	Person days/ha
Stones available in field	Small (cross-section 0.05 m <sup>2</sup> )	35	70	25	50
	Medium (cross-section 0.08 m <sup>2</sup> )	55	110	40	80
Stones transported locally	Small (cross-section 0.05 m <sup>2</sup> )	35	105	25	75
(wheelbarrow etc.)	Medium (cross-section 0.08 m <sup>2</sup> )	55	165	40	120

Note: Labour requirements are very sensitive to availability of stone. The productivity figures quoted above are based on experience where suitable sized stones were available in-field (productivity 0.5 m<sup>3</sup> person-day) or in the immediate locality (productivity 0.33 m<sup>3</sup> person-day)^ These rates of productivity would decrease significantly if stone has to be transported over greater distances and/or is of too large a size and has to be broken.

### iii. Catchment: cultivated area ratio

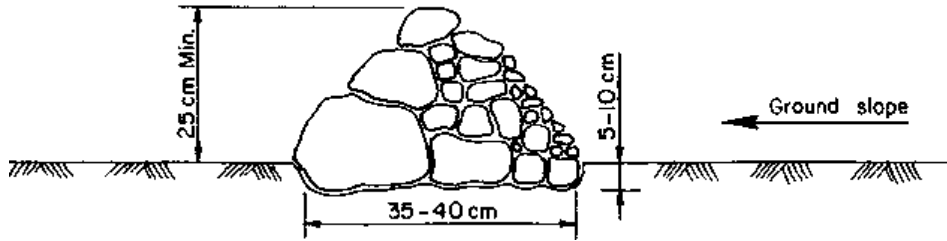
Contour stone bunds are a long slope technique relying on an external catchment. Theoretical catchment: cultivated area (C:CA) ratios can be calculated using the formula given in Chapter 4. Initially it is advisable to be conservative in estimation of areas which can be cultivated from any catchment. The area can be extended either downslope or upslope in subsequent cropping seasons, if appropriate.

### iv. Bund design

Although simple stone lines can be partially effective, an initial minimum bund height of 25 cm is recommended, with a base width of 35 - 40 cm. The bund should be set into a shallow trench, of 5 - 10 cm depth, which helps to prevent undermining by runoff. As explained in the construction details, it is important to incorporate a mixture of large and small stones. A common error is to use only large stones, which allow runoff to flow freely through the gaps in-between. The bund should be constructed according to the "reverse filter" principle - with smaller stones placed upstream of the larger ones to facilitate rapid siltation.

Bund spacings of 20 metres for slopes of less than 1%, and 15 metres for slopes of 1-2%, are recommended.

### **Figure 47 Contour stone bund: dimensions**



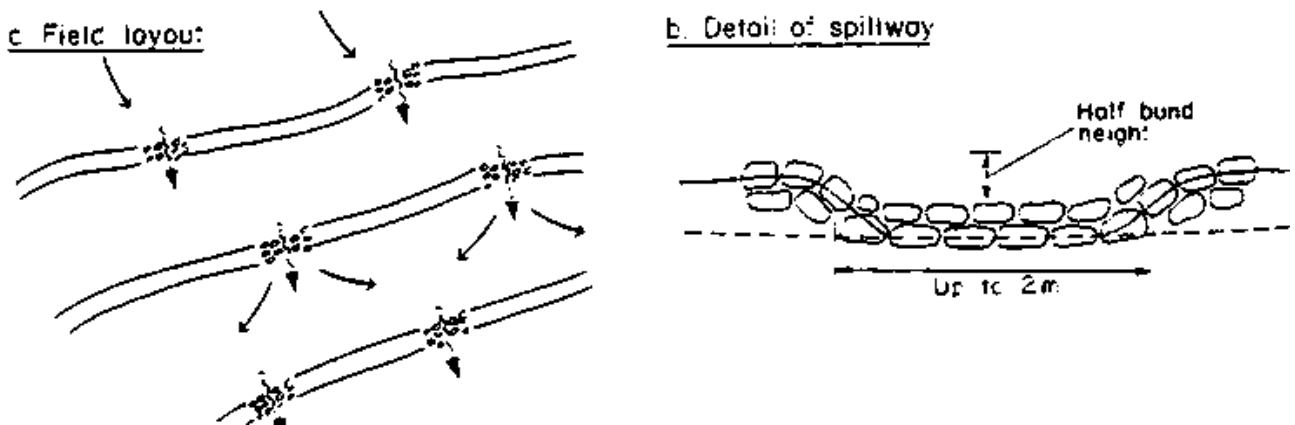
v. Quantities and labour

Table 24 gives details of the quantities of stone involved in bunding and the associated labour.

vi. Design variations

Where there is not enough stone readily available, stone lines can be used to form the framework of a system. Grass, or other vegetative material, is then planted immediately behind the lines and forms, over a period of time, a "living barrier" which has a similar effect to a stone bund. Alternatively, earth contour bunds can be constructed, with stone spillways set into them (Figure 48).

**Figure 48. Design variation: contour earth bunding with stone spillway**



### 5.7.3 Layout and construction

#### Step One

The average slope of the field is determined by a simple surveying instrument such as a water level or a line level (see Appendix) to decide on the spacing of the bunds. Each contour line is then set out and pegged individually. A horizontal spacing of approximately 20 metres apart is recommended for slopes of up to 1%, and 15 metres apart for 1 - 2% slopes. Because of variations in the slope, the lines may come closer together, or diverge at some points. The horizontal spacings recommended are the average distances apart. If labour is a limiting factor, farmers can start with a single bund at the bottom of their fields and work progressively upslope in seasons to come.

#### Step Two

After the exact contour is laid out, the line should be smoothed by moving individual pegs up or downslope. As a guideline, for ground slopes of up to 1.0 % pegs can be moved 2 metres upslope or downslope to create a smoother curve. Not only will a gentle curve be easier to follow while ploughing, but also the amount of stone used for construction will be reduced.

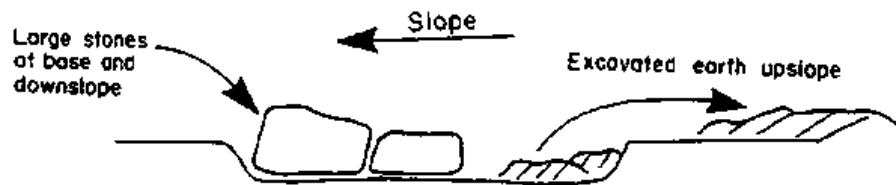
### Step Three

A shallow trench is now formed along the smoothed contour. The trench is made by hand tools, or ploughed by oxen and then excavated by hand. The trench need only be 5 -10 cm deep and equal to the base width of the bund (35 - 40 cm). The excavated soil is placed upslope.

### Step Four

Construction begins with large stones laid down at the base and the downslope side of the trench, and then smaller stones laid in front and on top of this "anchor" line. Small stones should be used to plug gaps between the larger ones. Where possible, a line of small or gravelly stones should run along the upslope face of the bund to create a fine filter. The key to a successful stone bund is to eliminate any large gaps between stones. In some areas it will be necessary to break large stones to produce the correct sizes of material.

Figure 49. Construction of stone bund



## 5.7.4 Maintenance

During heavy runoff events stone bunds may be overtopped and some stones dislodged. These should be replaced. A more common requirement is to plug any small gaps with small stones or gravel where runoff forms a tunnel through.

Eventually stone bunds silt-up, and their water harvesting efficiency is lost. It normally takes 3 seasons or more to happen, and occurs more rapidly where bunds are wider apart, and on steeper slopes. Bunds should be built up in these circumstances with less tightly packed stones, to reduce siltation, while maintaining the effect of slowing runoff.

Alternatively grasses can be planted alongside the bund. **Andropogon gyanus** is the best grass for this purpose in West Africa. It can be seeded, and the mature grass is used for weaving into mats. The grass supplements the stone bund and effectively increases its height.

## 5.7:5 Husbandry

Stone bunds in West Africa are often used for rehabilitation of infertile and degraded land. In this context it is recommended that the bunds be supported by a further technique - that of planting pits or "zai". These pits, which are usually about 0.9 m apart, are up to 0.15 m deep and 0.30 m in diameter. Manure is placed in the pits to improve

plant growth. The pits also concentrate local runoff which is especially useful at the germination and establishment phase.

As in the case of all cropping systems under water harvesting, an improved standard of general husbandry is important to make use of the extra water harvested. Manuring (as described above) is very important in fertility management. Also essential is early weeding: in areas where stone bunds are commonly used, late weeding is often a constraint to production.

### **5.7.6 Socio-economic factors**

On-farm stone bunding for crop production is quickly appreciated and adopted by farmers. The techniques involved, including simple surveying, can be easily learned. The amount of labour required is reasonable, and where groups are organized to work in turn on individual member's farms, fields can be transformed in a single day. The benefits of stone bunding are often clearly seen already in the first season - and this helps to make the system popular.

Nevertheless there are some problems which must be faced. Relatively rich farmers can make use of wage labour to treat their fields, and poorer farmers may lag behind. Differing availabilities of stones can lead to inequalities between neighbouring areas: not everyone can benefit in the same way. This leads to another problem - to what extent is the cost of stone transport justified?

#### **PROFILE: The Agroforestry Project, Yatenga, Burkina Faso**

The Agroforestry Project situated in Yatenga Province in the north of Burkina Faso, has been promoting contour stone bunding since 1980. The reduced rainfall in the Sahelian zones over the last two decades has left much of the land in this area barren and encrusted with a hard surface cap. Combined with increasing population pressure, the people were faced with a stark choice - to improve the land or to migrate.

Under the Agroforestry Project the traditional technique of stone bunding was improved, and farmers trained to lay out contours using a water level, and to build bunds more "scientifically". The results have been visible and impressive: farmers who have treated their land have obtained cereal yields up to twice that of their neighbours. The area of land treated has been increased from 150 ha in 1982 to approximately 5000 ha in 1987.

## **5.8 Permeable rock dams**

### **5.8.1 Background**

Permeable rock dams are a floodwater farming technique where runoff waters are spread in valley bottoms for improved crop production. Developing gullies are healed at the same time. The structures are typically long, low dam walls across valleys. Permeable rock dams can be considered a form of "terraced wadi", though the latter term is normally used for structures within watercourses in more arid areas.

Interest in permeable rock dams has centred on West Africa - Burkina Faso in particular - and has grown substantially in the latter part of the 1980s. This technique - "digue filtrante" in French - is particularly popular where villagers have experienced the gullying of previously productive valley bottoms, resulting in floodwater no longer spreading naturally. The large amount of work involved means that the technique is labour

intensive and needs a group approach, as well as some assistance with transport of stone.

## 5.8.2 Technical Details

### i. Suitability

Permeable rock dams for crop production can be used under the following conditions:

Rainfall: 200 -750 mm; from arid to semi-arid areas.

Soils: all agricultural soils - poorer soils will be improved by treatment.

Slopes: best below 2% for most effective water spreading.

Topography: wide, shallow valley beds.

The main limitation of permeable rock dams is that they are particularly site-specific, and require considerable quantities of loose stone as well as the provision of transport.

### ii. Overall configuration

A permeable rock dam is a long, low structure, made from loose stone (occasionally some gabion baskets may be used) across a valley floor. The central part of the dam is perpendicular to the watercourse, while the extensions of the wall to either side curve back down the valleys approximately following the contour. The idea is that the runoff which concentrates in the centre of the valley, creating a gully, will be spread across the whole valley floor, thus making conditions more favourable for plant growth. Excess water filters through the dam, or overtops during peak flows. 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.

### iii. Catchment: cultivated area ratio

The calculation of the C:CA ratio is not necessary as the catchment area and the extent of the cultivated land are predetermined. However, the catchment characteristics will influence the size of structure and whether a spillway is required or not.

**Figure 50. Permeable rock dams: general layout (Source: Critchley and Reij 1989)**

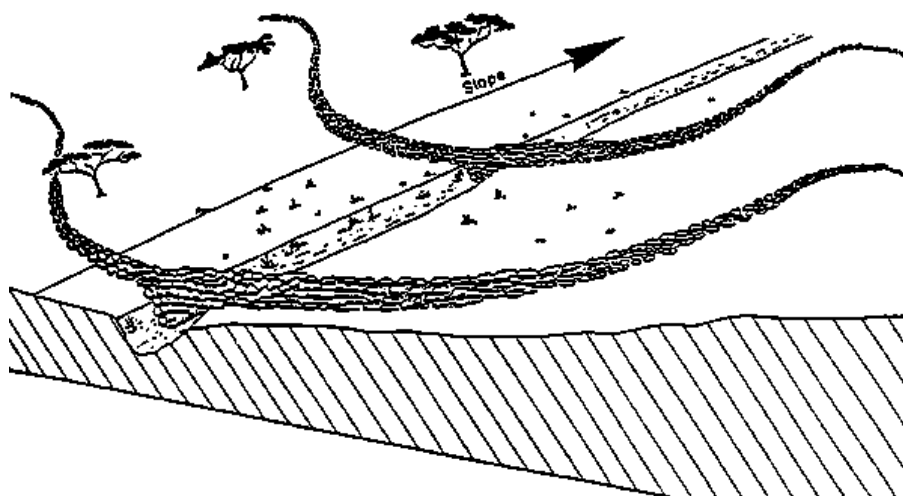


Figure 51. Dam dimensions

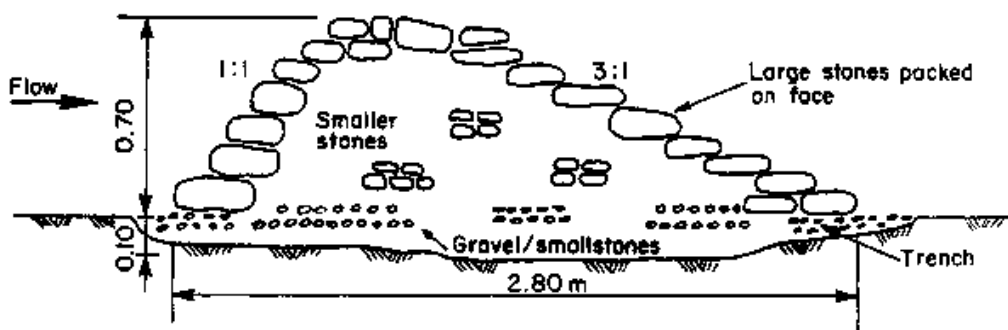


Table 25 QUANTITIES FOR PERMEABLE ROCK DAMS

Land slope (%)	Spacing between dams* (m)	Volume of stone per ha cultivated (m <sup>3</sup> )
0.5	140	70
1.0	70	140
1.5	47	208
2.0	35	280

\* vertical intervals between adjacent dams = 0.7 m

#### iv. Dam design

The design specifications given below are derived from a number of permeable rock dam projects in West Africa. Each project varies in detail, but the majority conform to the basic pattern described here.

The main part of the dam wall is usually about 70 cm high although some are as low as 50 cm. However, the central portion of the dam including the spillway (if required) may reach a maximum height of 2 m above the gully floor. The dam wall or "spreader" can

extend up to 1000 metres across the widest valley beds, but the lengths normally range from 50 to 300 metres. The amount of stone used in the largest structures can be up to 2000 tons.

The dam wall is made from loose stone, carefully positioned, with larger boulders forming the "framework" and smaller stones packed in the middle like a "sandwich". The sideslopes are usually 3:1 or 2:1 (horizontal: vertical) on the downstream side, and 1:1 or 1:2 on the upstream side. With shallower side slopes, the structure is more stable, but more expensive.

For all soil types it is recommended to set the dam wall in an excavated trench of about 10 cm depth to prevent undermining by runoff waters. In erodible soils, it is advisable to place a layer of gravel, or at least smaller stones, in the trench.

#### v. Quantities and labour

The quantity of stone, and the labour requirement for collection, transportation and construction depends on a number of factors and vary widely. Table 25 gives the quantity of stone required per cultivated hectare for a series of typical permeable rock dams under different land gradients.

The figures were calculated for a rock dam with an average cross section of 0.98 m<sup>2</sup> (70 cm high, base width of 280 cm) and a length of 100 metres. The vertical interval between dams is assumed to be 0.7 metre, which defines the necessary spacing between adjacent dams (see Figure 54).

Transport of stones by lorries from the collection site to the fields in the valley is the normal method. Considerable labour may be required to collect, and sometimes break, stone. Labour requirements, based on field estimates, are in the range of 0.5 cubic metres of stone per person/day - excluding transport.

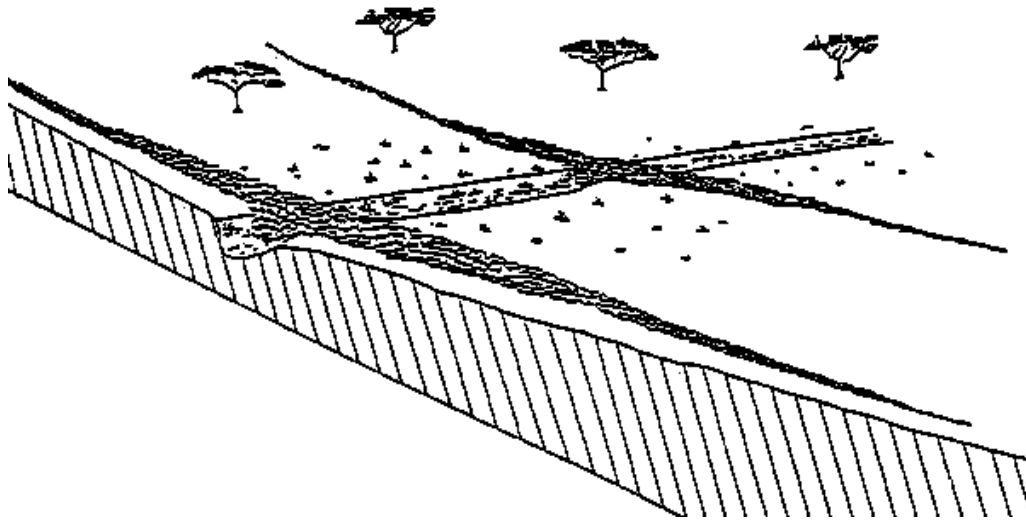
#### vi. Design variations

Where permeable rock dams are constructed in wide, relatively flat valley floors, they are sometimes made straight across - in contrast to the usual design where the spreader bunds arch back from the centre to follow the contour. With straight dams, the height of the wall decreases from the centre towards the sides of the valley to maintain a level crest.

Permeable rock dams are similar in many respects to the "terraced wadis" traditionally used in North Africa and the Middle East. However, the terraced wadi system is used in more arid regions, across clearly defined watercourses (Gilbertson 1986; Reij 1988). Cross-wadi walls of stone retain runoff to depths of up to 50 cm, with the excess flowing over spillways into successive terraces below. Crops and fruit trees utilize the residual moisture.

The "Liman" system, principally reported from Israel, is used on flood plains or in broad "wadi" beds. Bunds, often of earth, pond water to depths of 40 cm, and excess drains around an excavated spillway. "Limanim" (plural of Liman) may be constructed in series along a wadi bed. This technique is found where rainfall is as low as 100 mm per annum, and is used for crops, fruit trees or forestry.

**Figure 52 Permeable rock dams: alternative layout (Source: Critchley and Reij 1989)**



### **5.8.3 Layout and construction**

#### **Step One**

Site selection depends both on the beneficiaries and the technicians. Theoretically it is best to start at the top of the valley, though this may not always be the people's priority. After site identification it is necessary to determine whether the structure needs a defined spillway: as a rule of thumb no spillway is required if the gully is less than one metre deep. For greater depths, a spillway is recommended. Gullies of over two metres depth pose special problems and should be only tackled with caution. It is important not to build a permeable rock dam immediately above a gully head, as there is the risk that the dam will fall into the gully if continued erosion causes the gully head to cut back.

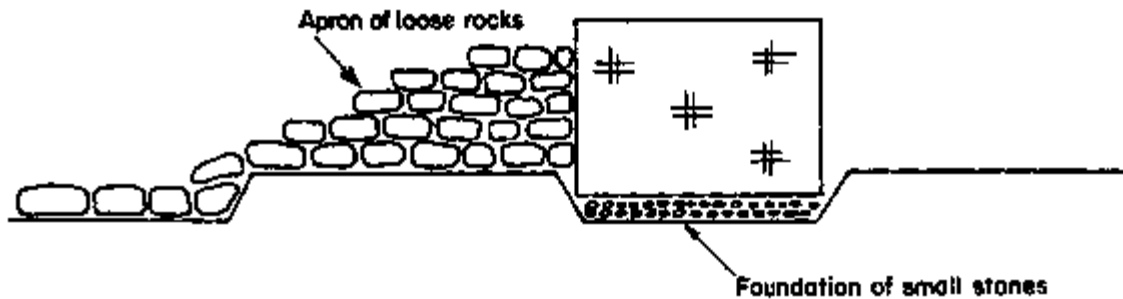
#### **Step Two**

Where a spillway is required, this should be built first. Gabions are best for spillways, as loose stone is easily destabilized by heavy floods. The following should be noted:

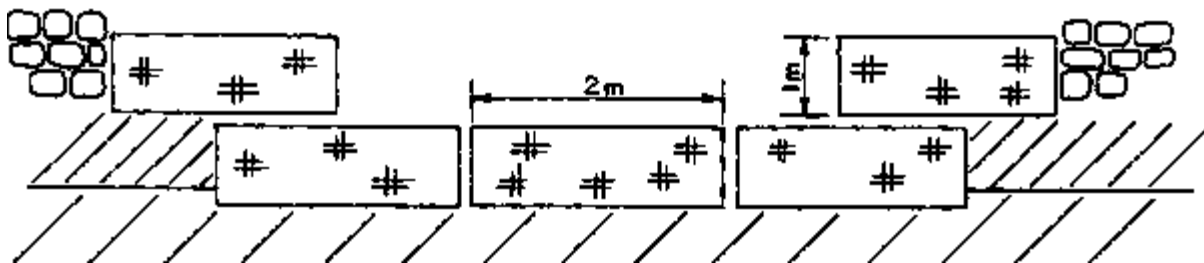
- a. A foundation of small stones, set in a trench, is required.
- b. An apron of large rocks is needed to break the erosive force of the overflow.
- c. The downstream banks of the watercourse should be protected by stone pitching to prevent enlargement of the gully.

**Figure 53. Gabion spillway**

**a. Cross section**



**b. Front elevation**



**Step Three**

The alignment of the main dam walls can be marked out, starting at the centre of the valley (where there may/may not be a spillway). This alignment is ideally along the contour, or as close to the contour as possible. Thus the extension arms sweep backwards in an arc like the contours of a valley on a map. The arms end when they turn parallel to the watercourse. The contour can be laid out simply using a water tube or line level (see appendix).

**Step Four**

A typical cross section (taken from the design of the PATECORE project in Burkina Faso - see profile at end of chapter) is recommended for general use. This is of 280 cm base width, 70 cm height and side slopes of 1:1 upstream and 3:1 downstream. Larger cross sections may be required dependent on catchment characteristics.

The first action after aligning the extension arms of the dam is to dig a trench at least 10 cm deep and 280 cm wide (according to the base width of the bund). The earth should be deposited upslope and the trench filled with gravel or small stones.

**Step Five**

The skill of construction is in the use of large stones (preferably of 30 cm diameter or more) for the casing of the wall. This should be built up gradually following the required

sideslope, and the centre packed with smaller stones. The whole length of the bund should be built simultaneously, in layers. This layered approach reduces the risk of damage by floods during construction.

Earth should not be mixed with the stone because it may be washed out and thus destabilize the structure. It is particularly important to pack the small stones well at the lower levels to increase the rate of siltation. The structure is finished off with a cap of large stones. It should be possible to walk on the structure without any stones falling off. The dam wall should be level throughout its length, which can be checked by the use of a water tube or line level.

### **Step Six**

If a series of permeable rock dams is to be built, an appropriate vertical interval (VI) should be selected. Technically speaking it is correct to:

- a. start at the top of the valley and work down;
- b. use a VI equal to the height of the structure - so that the top of one structure is at the same level as the base of the one above it (see Figure 54).

Therefore for dams of 70 cm height, the VI should theoretically be 70 cm. However in practice this may not be practicable due to the amount of stone and labour involved. As a compromise, a V.I. of 100 cm might be more realistic. Even wider spacing could be adopted, and the "missing" structures "filled in" afterwards. The vertical interval can be determined most easily by the use of a line-level.

The horizontal spacing between adjacent dams can be determined from the selected VI and the prevailing land slope according to the formula:

$$HI = (VI \times 100) / \% \text{slope}$$

where:

HI = horizontal interval (m)

VI = vertical interval (m)

% slope = land gradient expressed as a percentage.

For example, for a VI of 0.7 m and a 1% land slope,

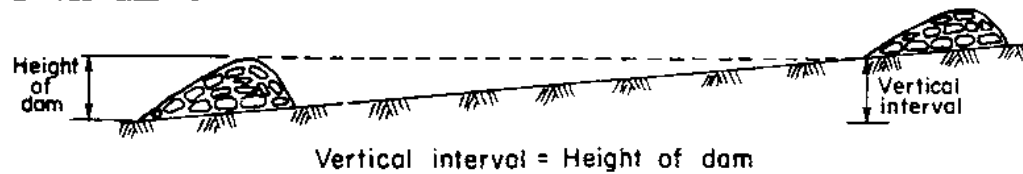
$$HI = (0.7 \times 100) / 1 = 70 \text{ metres}$$

For a VI of 0.7 m and a 2% land slope,

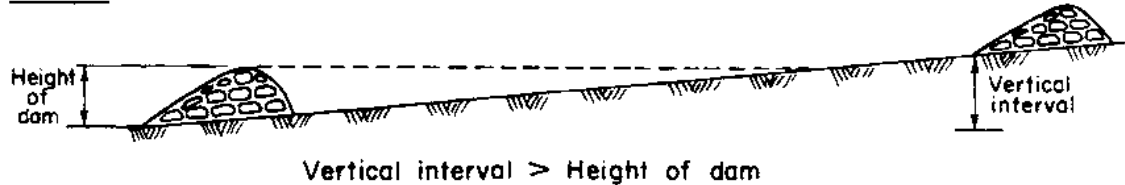
$$HI = (0.7 \times 100) / 2 = 35 \text{ metres}$$

**Figure 54. Spacing of rock dams (Source: Berton 1989)**

#### a. Ideal spacing



#### b. Usual



### 5.8.4 Maintenance

The design given above, with its low side slopes and wide base should not require any significant maintenance work provided the described construction method is carefully observed. It will tolerate some overtopping in heavy floods. Nevertheless there may be some stones washed off, which will require replacing, or tunneling of water beneath the bund which will need packing with small stones. No structure in any water harvesting system is entirely maintenance free and all damage, even small, should be repaired as soon as possible to prevent rapid deterioration.

### 5.8.5 Husbandry

Permeable rock dams improve conditions for plant growth by spreading water, where moisture availability is a limiting factor. In addition, sediment, which will build up behind the bund over the seasons, is rich in nutrients, and this will further improve the crop growth.

This technique is used exclusively for annual crops. In the sandier soils, which do not retain moisture for long, the most common crops are millet and groundnuts. As the soils become heavier, the crops change to sorghum and maize. Where soils are heavy and impermeable, waterlogging would affect most crops, and therefore rice is grown in these zones. Within one series of permeable rock dams, several species of crop may be grown, reflecting the variations in soil and drainage conditions.

### 5.8.6 Socio-economic factors

The implementation of permeable rock dams raises several important socio-economic issues. Many of these are rather specific to this technique. This is because permeable rock dams are characterized by:

- large quantities of stone needed;
- outside assistance often necessary for transport of stone;
- limited number of direct beneficiaries;
- siting is often determined by the people rather than the technicians.

As the structures cannot be made by individual farmers, it is necessary to cooperate in construction. It would be ideal if a village committee can be formed to co-ordinate efforts

and discuss the situation of priority sites and beneficiaries. It is unrealistic to expect implementation of such a programme without outside help for transport of stones, which should be provided free of charge to the beneficiaries. Long-term sustainability and replicability of the form of development would best be promoted if beneficiaries could establish revolving funds for the hire or purchase of transport.

**PROFILE: Permeable Rock Dams on the Central Plateau of Burkina Faso**

Traditionally the gently sloping valleys of the Central Plateau in Burkina Faso have been the most productive farmland, due to the natural flooding during the rains. However much of the surrounding land has become degraded and the increased runoff has caused gullies in the valley bottoms. The water no longer spreads and the land is parched and eroding.

In the mid 1980s a number of projects began to test permeable rock dams across these valleys, with impressive results. The villagers have been very enthusiastic and there is great demand for assistance. A recently established project, PATECORE, at Kongoussi specializes in permeable rock dams, or "filtering floodwater spreaders" as the project calls them.

The dams are built according to the specifications given in the layout and construction section of this chapter, and much emphasis is put on careful construction. All the labour is provided by the local community, who are fully involved in site selection and village land-use planning. Villagers are trained in setting out and construction supervision. The project supplies transport of stone, by lorries with removable skips, free of charge.

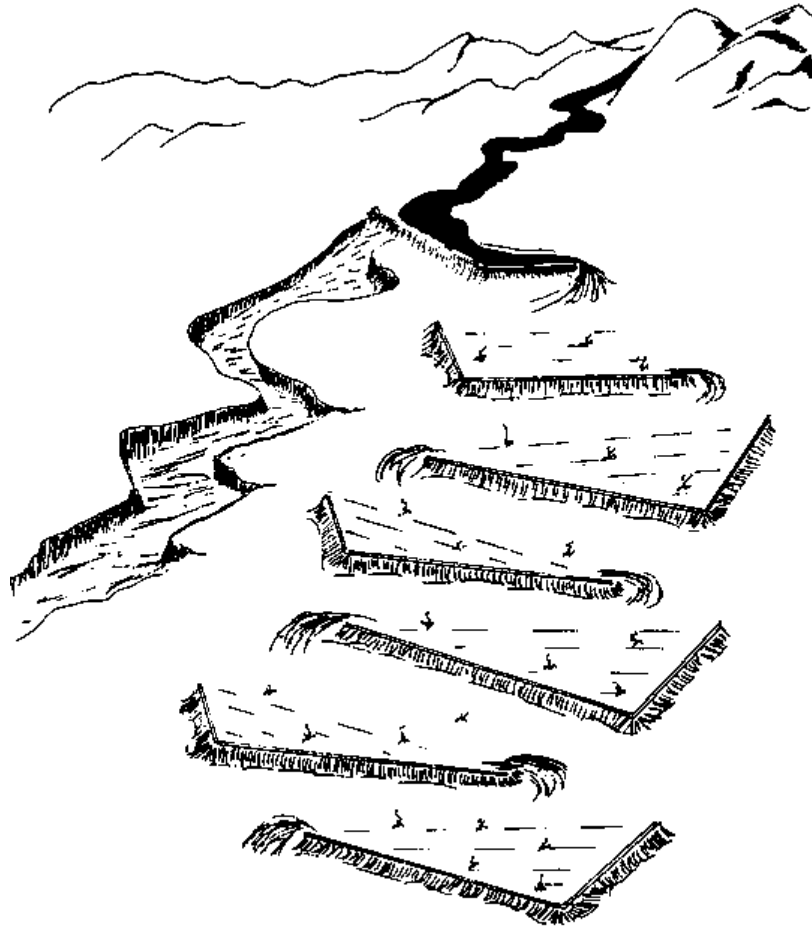
## **5.9 Water spreading bunds**

### **5.9.1 Background**

Water spreading bunds are often applied in situations where trapezoidal bunds are not suitable, usually where runoff discharges are high and would damage trapezoidal bunds or where the crops to be grown are susceptible to the temporary waterlogging, which is a characteristic of trapezoidal bunds. The major characteristic of water spreading bunds is that, as their name implies, they 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. 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 55 Flow diversion system with water spreading bunds in Pakistan (Source: Nas 1980)**



## 5.9.2 Technical Details

### i. Suitability

Water spreading bunds can be used under the following conditions:

Rainfall: 100 mm - 350 mm; normally hyper-arid/arid areas only.

Soils: alluvial fans or floodplains with deep fertile soils.

Slopes: most suitable for slopes of 1% or below.

Topography: even.

The technique of floodwater farming using water spreading bunds is very site-specific. The land must be sited close to a wadi or another watercourse, usually on a floodplain with alluvial soils and low slopes. This technique is most appropriate for arid areas where floodwater is the only realistic choice for crop or fodder production.

### ii. Overall configuration

Two design examples are given. The first is for slopes of less than 0.5%, where the structures are merely straight open ended bunds sited across the slope, which "baffle" (slow and spread) the flow. The second, for slopes greater than 0.5%, is a series of

graded bunds, each with a single short upslope wing, which spread the flow gradually downslope. In each case, crops or fodder are planted between the bunds.

iii. Catchment: cultivated area ratio

The precise calculation of a catchment: cultivated area ratio is not practicable or necessary in the design of most water spreading bunds. The reasons are that the floodwater to be spread is not impounded - much continues to flow through the system, and furthermore often only part of the wadi flow is diverted to the productive area. Thus the quantity of water actually utilized cannot be easily predicted from the catchment size.

iv. Bund design

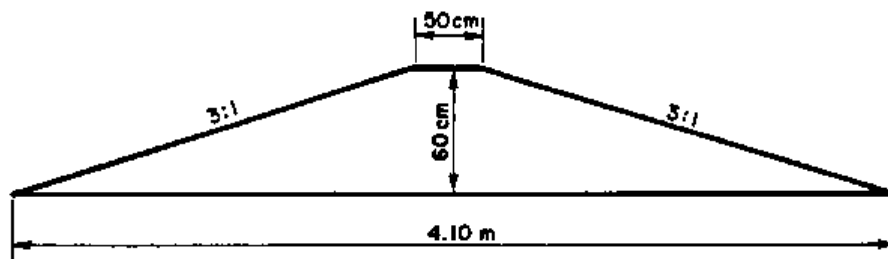
a. Slopes of less than 0.5%

Where slopes are less than 0.5%, straight bunds are used to spread water. Both ends are left open to allow floodwater to pass around the bunds, which are sited at 50 metres apart. Bunds should overlap - so that the overflow around one should be intercepted by that below it. The uniform cross section of the bunds is recommended to be 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 recommended.

b. Slopes of 0.5% to 1.0%

In this slope range, graded bunds can be used (Figure 59). Bunds, of constant cross-section, are graded along a ground slope of 0.25%. Each successive bund in the series downslope is graded from different ends. A short wingwall is constructed at 135° to the upper end of each bund to allow interception of the flow around the bund above. This has the effect of further checking the flow. The spacing between bunds depends on the slope of the land. Examples for different slopes are given in Figures 58 and 59. The bund cross section is the same as that recommended for contour bunds on lower slopes. The maximum length of a base bund is recommended to be 100 metres.

**Figure 56 Bund dimensions**



v. Quantities and labour

Table 26 gives details of the quantities and labour involved in construction of water spreading bunds for different slope classes. A bund cross section of 1.38 square metres is assumed. Labour requirements are relatively high because of the large sized structures requiring soil to be carried.

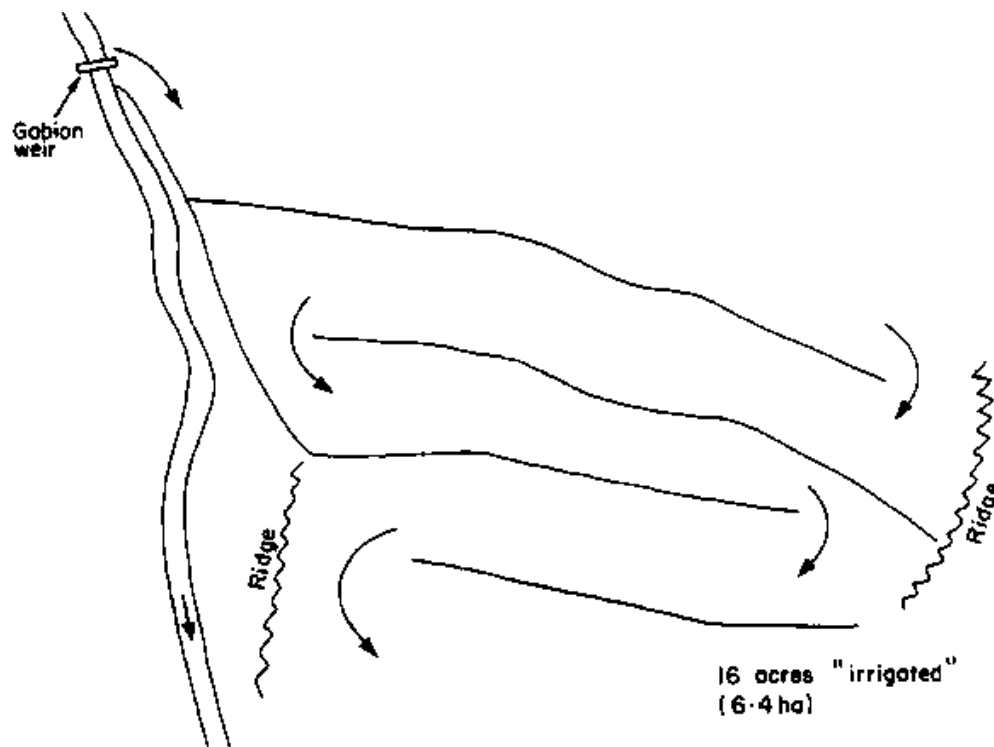
**Table 26. QUANTITIES OF EARTHWORKS FOR WATER SPREADING BUNDS**

Slope class/technique	No. bunds per ha	Total bund length (m)	Earthworks (m <sup>3</sup> /ha)
<b>Level bunds</b>			
- below 0.5%	2	200	275
<b>Graded bunds</b>			
- 0.5%	2	220	305
- 1.0%	3	330	455

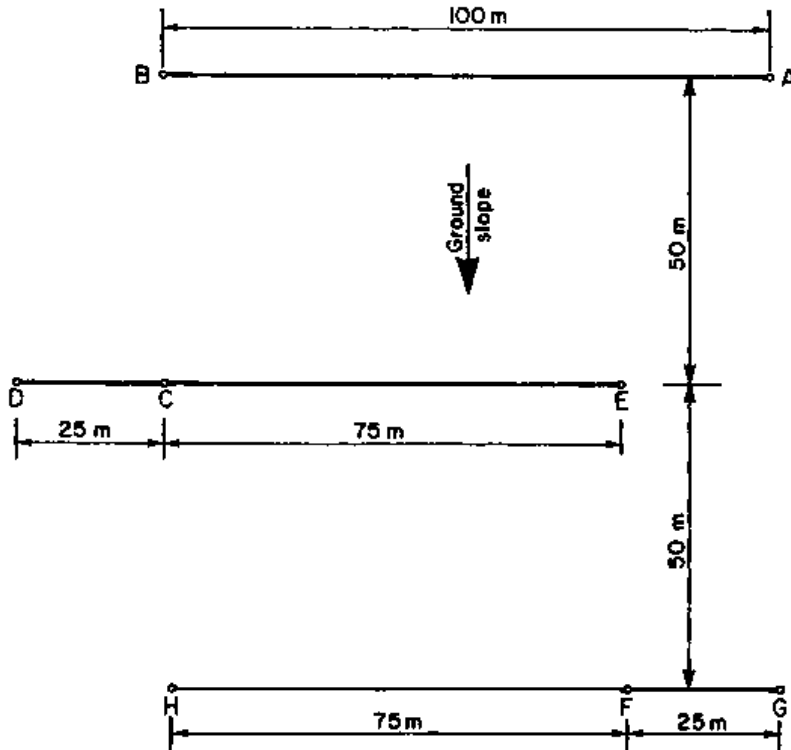
vi. Design variations

There are many different designs for water spreading bunds possible, and that given in this manual is merely one example. Much depends on the quantity of water to be spread, the slope of the land, the type of soil and the labour available. Existing systems are always worth studying before designing new systems.

**Figure 57. Impala Pilot Water Spreading Scheme, Turkana, Kenya (Source: Fallon 1963)**



**Figure 58. Setting out of level bunds: groundslope < ft 5%**



### 5.9.3 Layout and construction

#### Step One

The first step is to measure the slope of the land, in order to select the appropriate bunding system. This can be done most simply with an Abney level, or with a line level, as described in the appendix.

#### Step Two

Straight bunds are used for ground slopes of less than 0.5% and are spaced at 50 m intervals. The bunds should, however, be staggered as shown on Figure 58, which also illustrates the setting out procedure.

Having selected the starting point at the upslope end of the bund system point A is marked with a peg. Using a line or water level and, if necessary, a tape, point B is pegged on the contour 100 m away from A. Line AB is then the centreline of the first bund and should be marked with pegs or stones.

Point C is 50 m downslope from point B and can be established by marking of a right angle perpendicular to AB, using a wooden triangular right angle frame (sides: 100 cm, 60 cm, 80 cm) and a tape. Point D is then established with level and tape at the same ground level as C, at a distance of 25 m from C to allow overlap with AB. Point D is then pegged. Point E is also on the same ground level as point C, but 75 m distant in the opposite direction to point D. The line DE is the centreline of the second bund and should be marked with pegs or stones. Point F is 50 m downslope of point E and is established in a similar manner as point C. Point G is then established on the same

ground level as point F but 25 m distant to allow overlap with DE. Similarly point H is at the same ground level as point F but 75 m distant, in the opposite direction to point G.

This process can be repeated down the slope to lay out the field of bunds.

### **Step Three**

For ground slopes above 0.5% bunds aligned with a 0.25% gradient are used and are termed "graded bunds".

Having selected the starting point (A) at the upslope end of the bund system, it is marked with a peg. Using a line, or water level, and a tape, the line AB is set out on a 0.25% gradient. As the distance AB is 100 m, the ground level at B is 25 cm below that at A. Point B is then marked with a peg and the line AB, forming the centreline of the first bund, is marked with pegs or stones.

Point C, on the centre line of the second bund, is at a distance of 25 m immediately downslope of point B. It is most easily found by using the line or water level to establish the maximum field gradient between B and C, and by measuring from B through that point a distance of 25 m.

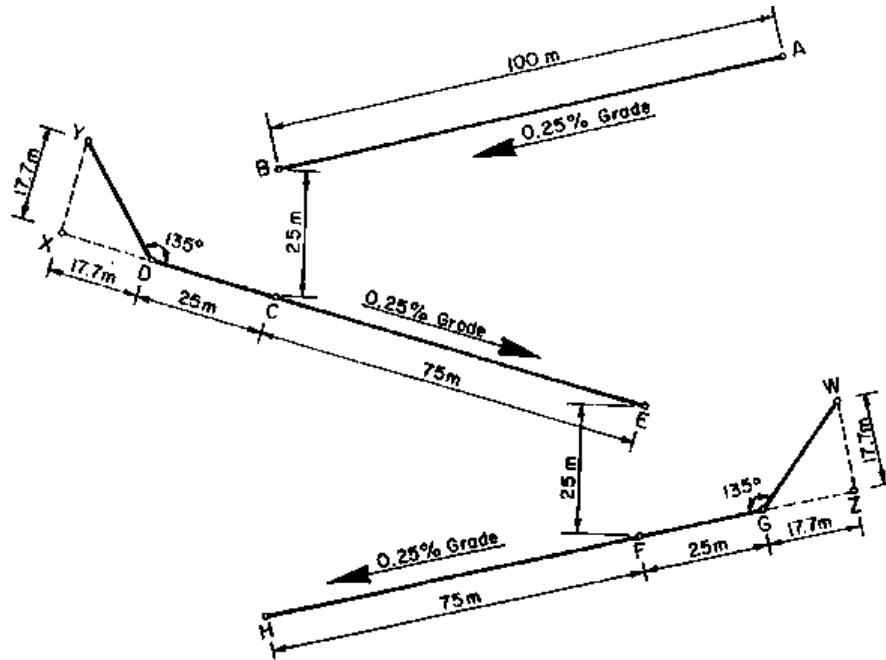
Having established C the 0.25% slope line is again established and point D located along that line 25 m from C. Note that point D will be at a slightly higher ground level than point C and should provide overlap with the line AB, as shown in Figure 59. The other end of the bund centreline, point E, is 75 m on the opposite side of C along the 0.25% slope line. The points D and E should be pegged and mark the centreline of the second bund.

The wing bund always starts from the overlapping end of the base bund, in this case point D. The wing bund is 25 m long and at an angle of 135° to the base bund. It is most easily found by extending the line ED a distance of 17.7 m from D to give point X. Point Y is then a distance of 17.7 m upslope from point X, and at a right angle to the line XDE. It can be located using a tape and right angle template as described above.

The first point on the next bund line, point F, is located in a similar manner to point E and the bend centreline HFG can be set out as above. The end of the wing bund, W, can be located in a similar manner as Y.

This process is continued down the field.

**Figure 59. Setting out of graded bunds: groundslope > 0.5%**



#### Step Four

Having marked out the centrelines of the bunds, the limits of fill can be marked by stakes or stones placed at a distance of 2.05 m on either side of the centrelines.

#### Step Five

Construction begins at the top of the field as in all water harvesting systems. Earth should be excavated from both sides to form the bunds, and in the shallow trenches formed, earth ties should be foreseen at frequent intervals to prevent scouring. The earth beneath the bunds should be loosened to ensure a good mating with the bund.

The bunds are constructed in two layers of 30 cm each, and compaction by trampling is recommended on the first course and again when the bund is complete.

#### Step Six

At the ends of the contour bunds, and at the tip of the wingwalls of the graded bunds, stone pitching should be placed - if loose stone is available - to reduce potential damage from flow around the bunds.

### 5.9.4 Maintenance

As is the case in all water harvesting systems based on earth bunds, breaches are possible in the early stages of the first season, before consolidation has taken place. Thus there must be planning for repair work where necessary and careful inspection after all runoff events. In subsequent seasons the risk of breaching is diminished, when the bunds have consolidated and been allowed to develop vegetation - which helps bind the soil together, and reduces direct rainfall damage to the structures. Nevertheless with systems which depend on floodwater, damaging floods will inevitably occur from time to time, and repairs may be needed at any stage.

### 5.9.5 Husbandry

Water spreading bunds are traditionally used for annual crops, and particularly cereals. Sorghum and millet are the most common. One particular feature of this system, when used in arid areas with erratic rainfall, is that sowing of the crop should be undertaken in response to flooding. The direct contribution by rainfall to growth is often very little. Seeds should be sown into residual moisture after a flood, which gives assurance of germination and early establishment. Further floods will bring the crop to maturity. However if the crop fails from lack of subsequent flooding - or if it is buried by silt or sand (as sometimes happens) - the cultivator should be prepared to replant. An opportunistic attitude is required.

Because water spreading usually takes place on alluvial soils, soil fertility is rarely a constraint to crop production. Weed growth however tends to be more vigorous due to the favourable growing conditions, and thus early weeding is particularly important.

### 5.9.6 Socio-economic Factors

As the implementation of water spreading systems is a relatively large-scale exercise, consideration has to be given to community organization. One particular problem is that the site of the activity may be distant from the widely scattered homes of the beneficiaries.

In areas where crop production is a novelty it may be risky to provide incentives such as food for work rations to potential beneficiaries participating in the construction of such a crop production system. It has often been experienced that people consider it mainly as a job opportunity and lose any interest in the scheme once the project (and the incentives!) have come to an end. Once again this highlights the potential danger of incentives, rather than genuine motivation, which should be the driving force.

#### **PROFILE Water Spreading in Eastern Sudan**

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

The improvements being introduced are large earth diversion embankments in the main or subsidiary channels, and then a series of spreading bunds or "terraces". These bunds, are usually sited on, or approximately on, the contour, and spread the diverted flow. The spacing between bunds, in the typically almost flat landscape, is not fixed but can be quite wide - up to 200 metres apart. Bunds are usually up to 150 metres long, and minimum of 75 cm in height. Some machinery is employed, but manual labour supported by incentives is also used.

## 6. Husbandry

### 6.1 Introduction

The production aspects of rainwater harvesting systems for crops and trees are outlined in the sections which follow. A brief note is also included about grassland and range. Water harvesting improves growth by increasing the availability of water to plants in dry areas. However there is little point investing in rainwater harvesting structures unless attention is also given to other aspects of husbandry. Plants which are well nourished, cleanly weeded and protected from pests and diseases will respond best to the extra water.

### 6.2 Crops

#### 6.2.1 General

Water harvesting helps crops by providing extra moisture at different stages of growth - although timing cannot be controlled. Periods when the extra moisture can make a significant difference are:

- around sowing time when germination and establishment can be improved;
- during a mid-season dry spell when a crop can be supported until the next rains;
- while the crop is at the vital stages of flowering and grainfill.

#### 6.2.2 Crop choice

The most common cereal crops grown under water harvesting are:

- 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 waterlogging - which is a common occurrence in some water harvesting systems.
- Pearl Millet (**Pennisetum typhoides**) is grown in the drier areas of West Africa and India, and apart from being drought tolerant, it matures rapidly.
- Maize (**Zea mays**) is occasionally grown under water harvesting but is neither drought adapted nor waterlogging tolerant - but in parts of East and Southern Africa it is the preferred food grain, and farmers are often reluctant to plant millet or sorghum instead.

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 radiata**), lablab (**Lablab purpureus**), and groundnut (**Arachis hypogea**). All are relatively tolerant of drought and are fast maturing.

#### 6.2.3 Fertility

In dry areas soil fertility is usually the second most limiting production factor after moisture stress. The improvement in the supply of water available to plants under water harvesting can lead to depletion of soil nutrients. Therefore it is very important to maintain levels of organic matter by adding animal manure or compost to the soil. Inorganic fertilizers are seldom economic for subsistence crops grown under water harvesting.

Crop rotation helps maintain the fertility status. 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.

Some water harvesting systems actually harvest organic matter from the catchment and therefore build up fertility. This can most clearly be seen with stone bunding techniques which filter out soil and other organic particles, thereby building up fertile deposits.

### 6.2.4 Other husbandry factors

- 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.
- Early planting makes the best use of limited rainfall. In some areas it may be best to plant seeds before the rains arrive. This technique is known as "dry planting".
- "Opportunistic" or take-a-chance planting of a quick legume crop like cowpeas can make use of late season or out of season rainstorms.
- Low plant populations in themselves can improve yields in low rainfall zones, and therefore spacing of crops is another important consideration.

## 6.3 Trees

### 6.3.1 General

Rainwater harvesting is used to help tree seedlings become established in dry areas. The microcatchment technique concentrates water around the seedlings, and make a considerable difference to growing conditions at this vital early stage. In semi-arid areas, tree seedlings in the natural state usually germinate and grow only in years of above average rainfall - water harvesting imitates these conditions.

### 6.3.2 Choice of species

Table 27 summarizes the most important characteristics of the most commonly planted trees in semi-arid areas of Africa and India.

**Table 27. CHARACTERISTICS OF COMMONLY PLANTED TREE SPECIES**

Species	Characteristics
<b>Acacia albida</b>	"The" agroforestry tree of West Africa. Genuinely multi- purpose. Pods for fodder. Needs water table. Slow at first.
<b>Acacia nilotica</b>	Widespread in India and Africa. Likes deep soils and water table. Good fuel/fodder. Quite quick growing.
<b>Acacia saligna</b>	Introduced species from Australia. For dune fixation/fodder/windbreaks. Hardy. Fast growing.
<b>Acacia Senegal</b>	"Gum arabic" tree producing commercial gum. Good also for fuelwood/fodder. Direct seeding possible. Slow.

<b>Acacia seyal</b>	Likes low-lying areas with heavy soils which flood. Good forage/fuelwood. Quite fast early growth.
<b>Acacia tortilis</b>	"Umbrella thorn". Good fuelwood and charcoal. Branches for fencing. Pods good fodder. Fast once established.
<b>Albizia lebek</b>	From India. Small shade/amenity tree in Sahel. Needs high water table. Foliage for mulch. Rapid growth.
<b>Azadirachta indica</b>	Neem tree: from India/Burma. Grown for shade mainly but also good fodder/fuel. Fast growing.
<b>Balanites aegyptiaca</b>	"Desert date" widespread and ecologically "flexible". Fodder/edible fruit. Direct seeding possible. Slow.
<b>Cassia siamea</b>	Grown for shade, amenity, fuelwood and poles. Better with higher rainfall. Direct seeding possible. Quick.
<b>Casuarina equisetifolia</b>	Good on deep sands (also at coasts) so used for dune stabilization. Also fuelwood. Fast growing.
<b>Colophospermum mopane</b>	Indigenous to Southern Africa. Poles for construction and leaves for fodder. Firewood. Wood very hard.
<b>Eucalyptus camaldulensis</b>	From Australia. Best eucalypt for dry areas. Coppices well. Windbreak/fuelwood. Very quick growing.
<b>Prosopis chilensis</b>	Similar to, and often confused with, <i>P. juliflora</i> , see below.
<b>Prosopis cineraria</b>	Indigenous to NW India where grown as agroforestry tree. Fodder/fuel/building materials. Slow.
<b>Prosopis juliflora</b>	Very drought resistant and establishes naturally. May invade better areas. Coppices well. Good fuel supply. Pods for fodder. Quick growth.
<b>Ziziphus mauritiana</b>	"Jujube". Produces edible fruit. Can be grafted. Small tree. Branches for fencing. Slow growth.

### 6.3.3 Husbandry

Planting of more than one seedling at a planting station is usually a good idea. The reason is that the additional cost is small compared with the cost of the water harvesting structures and there is extra assurance of at least one seedling establishing. It is advisable to plant one seedling at the bottom of the pit/furrow and one by the side. The former may establish better in a dry year, and the second if conditions are wetter.

Direct seeding is a technique which saves all the nursery costs of producing seedlings. However it does mean that the trees will be slower growing in the early stages. Tree species which can successfully be direct seeded include **Balanites aegyptiaca** and **Prosopis juliflora**.

Weeding is only necessary close to the seedling. The area between the rows of trees should be allowed to grow grass (or even planted with an annual crop) so that some economic benefit can be gained in the first few years, before the trees mature.

## **6.4 Rangeland and fodder**

Although the use of water harvesting for range and fodder is relatively rare, there are some important points to make about husbandry. Often the most important factors are initial fencing and protection, followed by long-term grazing management.

Natural revegetation often gives satisfactory results without reseeding. However, where reseeding is used, it is usually best to collect seeds from local species known to do well in the area.

One advantage of range/grassland systems is that the roots of these perennial species tend to protect structures, and therefore maintenance requirements are reduced.

# **7. Socio-economic factors and project management**

## **7.1 Introduction**

This manual concentrates mainly on the technical aspects of rainwater harvesting systems, but it has been stressed throughout that it takes more than engineering and agronomy to make a project successful. Socio-economic factors are particularly important. Obviously, if the small scale farmer is the "customer" or beneficiary, then she/he must understand and be happy with a system which is appropriate, and which she/he is able to manage and maintain. This section looks at some socio-economic factors, and the implications they may have on project management.

## **7.2 Socio-economic factors**

### **7.2.1 People's priorities**

If the objective of rainwater harvesting projects is to assist resource-poor farmers to improve their production systems, it is important that the farmer's/agropastoralist's priorities are being fulfilled, at least in part. Otherwise success is unlikely. If the local priority is drinking water supply, for example, the response to water harvesting systems for crop production will be poor.

### **7.2.2 Participation**

It is becoming more widely accepted that unless people are actively involved in the development projects which are aimed to help them, the projects are doomed to failure. It is important that the beneficiaries participate in every stage of the project. When the project is being planned, the people should be consulted, and their priorities and needs assessed. During the construction phase the people again should be involved -supplying labour but also helping with field layouts after being trained with simple surveying instruments.

Throughout the course of the season it is helpful to involve people in monitoring, such as rainfall and runoff and recording tree mortality. A further participatory role is in maintenance, which should not be supported by incentives.

After the first season it is the farmers themselves who will often have the best ideas of modifications that could be made to the systems. In this way they are involved in evaluation, and in the evolution of the water harvesting systems.

### **7.2.3 Adoption of systems**

Widespread adoption of water harvesting techniques by the local population is the only way that significant areas of land can be treated at a reasonable cost on a sustainable basis. It is therefore important that the systems proposed are simple enough for the people to implement and to maintain. To encourage adoption, apart from incentives in the form of tools for example, there is a need for motivational campaigns, demonstrations, training and extension work.

### **7.2.4 Area differences**

It is tempting to assume that a system which works in one area will also work in another, superficially similar, zone. However there may be technical dissimilarities such as availability of stone or intensity of rainfall, and distinct socio-economic differences also. For example a system which is best adapted to hand construction may not be attractive to people who normally till with animals. If a system depends on a crop well accepted in one area - sorghum for example - this may be a barrier to acceptance where maize is the preferred food grain.

### **7.2.5 Gender and equity**

If water harvesting is intended to improve the lot of farmers in the poorer, drier areas, it is important to consider the possible effects on gender and equity. In other words, will the introduction of water harvesting be particularly advantageous to one group of people, and exclude others? Perhaps water harvesting will give undue help to one sex, or to the relatively richer landowners in some situations. These are points a projects should bear in mind during the design stage. There is little point in providing assistance which only benefits the relatively wealthier groups.

### **7.2.6 Land tenure**

Land tenure issues can have a variety of influences on water harvesting projects. On one hand it may be that lack of tenure means that people are reluctant to invest in water harvesting structures on land which they do not formally own. Where land ownership and rights of use are complex it may be difficult to persuade the cultivator to improve land that someone else may use later. On the other hand there are examples of situations where the opposite is the case - in some areas farmers like to construct bunds because it implies a more definite right of ownership.

The most difficult situation is that of common land, particularly where no well defined management tradition exists. Villagers are understandably reluctant to treat areas which are communally grazed - a point taken up in the next section.

### **7.2.7 Village land use management**

The whole question of land management by village communities has recently been acknowledged to be extremely important. Degraded land in and around villages can only be improved if land use management issues are faced by the communities themselves.

One of the techniques which can assist in rehabilitation of degraded land is water harvesting - but it is only one tool among several others and cannot be effective in isolation. Unless, for example, grazing controls are implemented, there is little point spending money on water harvesting structures for re-seeding.

## **7.3 Project management**

### **7.3.1 The project and the people**

The experience of projects related to water harvesting and soil conservation has shown that there is no substitute for dialogue with the farmers/villagers, and a continued close relationship throughout. Projects should always aim to learn from the people of the target area, in particular about local traditional technology.

It is essential that project authorities keep in mind the importance of people's priorities and participation. It is important that the benefits of the new systems should be apparent to the farmer as early as possible. For new techniques there is often a need for demonstration before people will understand and envisage their effectiveness. Motivation and promotion of awareness among the people with regard to the project objectives and how to achieve them are very important issues. It is sad but true that very often the people simply do not understand what a project is trying to achieve, or even what the meaning of the various structures is!

### **7.3.2 Project approach**

There are two basically different approaches with regard to water harvesting projects.

- The Demonstration, Training and Extension Approach:

The technology introduced by the project is relatively simple, and costs per hectare low. The intention is to promote systems which can be taken up and implemented by the people themselves, with a minimum of support. The philosophy behind this approach is that the people themselves must be the prime movers in the development of their own fields and local environment.

- The Implementational Approach:

In this approach the technology may be simple or complex, but it is implemented by the project itself. Machinery is often used, but some projects employ paid (or otherwise rewarded) labour. Costs are often relatively high. The intention is that the project will quickly and efficiently rehabilitate land for the people. The philosophy is that the people are simply unable to undertake the extent of work required using their own resources and therefore they require considerable or complete support to implement the project.

Experience shows that it is the first approach which offers the most hope for sustainability once the project has come to an end. Nevertheless there are situations where the introduction of appropriate machinery or support of some labour can be justified.

### **7.3.3 Machinery or hand labour**

This question has been touched on already - but it is an extremely important issue. The introduction of inappropriate heavy machinery for conservation structures has been a mistake repeated widely over Africa. Conversely some mechanization - especially where

animal traction is a component - can immeasurably speed up work rates and reduce drudgery.

The advantage of working by hand is that the people regard the techniques as within their capability. As long as part of the work is voluntary, they will be more willing to carry out maintenance. Nevertheless hand labour is slow, and labour shortages can be a serious constraint in some areas.

### 7.3.4 Flexibility of approach

Water harvesting and conservation projects should never have fixed work plans or rigid targets, at least not in the early stages of implementation. The reason quite simply is that it is unrealistic to plan for all contingencies, and arrogant to assume that the techniques and approaches planned from the outset cannot be improved. Learning from experience, and from interaction with the people, is a much better approach. Flexibility should be written into every project document.

### 7.3.5 Subsidies and incentives

Many water harvesting projects provide subsidies or incentives for construction. Several points need to be made about these:

- help and assistance should only be considered as stimuli to the programme; too big a subsidy to begin with can cripple future expansion and deter participation.
- it is important that in all cases the beneficiaries should make at least some voluntary contribution towards construction. The level of contribution should rise when incentives are provided.
- food-for-work is common in projects in drought-prone areas. It is not easy to manage food distribution and development work at the same time. Generally other incentives, such as tools for work, are preferable.
- incentives/subsidies should not be used for maintenance: this should be the responsibility of the beneficiaries.

### 7.3.6 Monitoring, evaluation and reporting

Monitoring, evaluation and reporting are often weak spots in water harvesting projects. Too many projects fail to collect data at even the most basic level. For example crop yields and tree heights are often just estimated. It is also very rare to find any information on the frequency or depth of water harvested. Without a basic monitoring system, projects are starving themselves of data for evaluation. Without clearly written reports, widely circulated, projects are denying to provide others with important information. A suggested monitoring format is presented in Table 28.

**Table 28. SUGGESTED MONITORING FORMAT FOR WATER HARVESTING PROJECTS**

1. HYDROLOGICAL DATA	
- rainfall (standard gauges at important sites)	
- runoff (at least visual recordings of occurrence)	

2. INPUTS	
- labour/machinery hours for	(a) construction
	(b) maintenance
	(c) standard agricultural operations
3. COSTS	
- labour/machinery use in	(a) construction
	(b) maintenance
	(c) standard agricultural operations
4. OUTPUTS	
- crops: yields of treated plots compared with controls	
- trees: survival and growth rates	
- grass/fodder: dry matter of treated plots compared with controls	
5. ACHIEVEMENTS	
- area (hectares) covered each season	
- number farmers/villagers involved/benefiting	
6. INCENTIVES/SUPPORT	
- quantity and costs	
7. TRAINING	
- number of training sessions	
- attendance/number of trained personnel	
8. EXTENSION	
- number of farmers visited	
- number of field days and attendance	

Note: SUMMARY SHEETS of data are very useful. These could include:

- labour/ha
- cost/ha
- average yield increases over controls
- total land treated and people benefitting

## **Appendix - Simple surveying techniques**

### **A.1 Use of the line level for surveying**

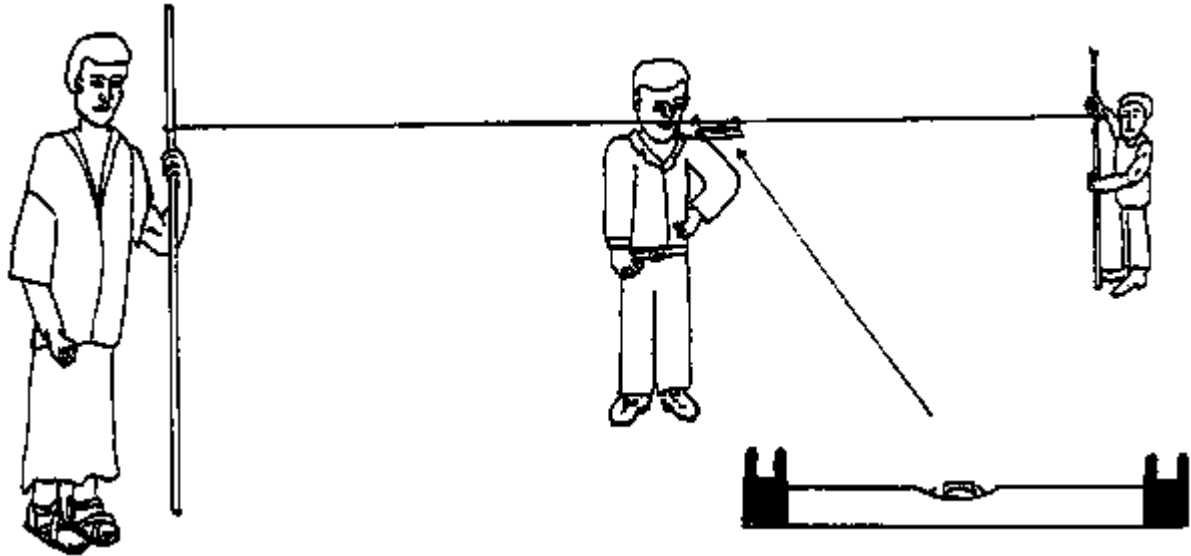
#### **Introduction**

1. The line level is a simple surveying instrument which can be used to lay out contours and gradients, and also to measure the slope of land. It is simple to operate and is easier to transport than other similar surveying tools such as the A-frame. It is especially quick and very accurate when used properly. However a line level does require three people to operate it.
2. A line level consists of two poles, between which a length of string is suspended. A spirit level is hung on the string. The level is the type used by builders, but has small hooks at either end.
3. The poles should be of even height (about 1.5 m) and the string (about 2 mm in diameter) and precisely 8 metres in length. A notch is made in each pole at exactly the same height (say 1.4 m above ground level) and the ends of the string tied around these notches.
4. The centre of the string (4 m from each end) is marked and the level itself is suspended there.

#### **Laying out a contour**

5. The poles are held apart by operators with the string extended and the spirit level positioned exactly in the middle of the string. When the bubble in the level is between the two marks this means that the poles are positioned on level points on the land - in other words on the contour. The poles must be held vertically.
6. To lay out a contour across a slope, the team begin at the edge of the field. The operator holding the pole at the field's edge (operator A) remains stationary while the operator holding the other pole (operator B) moves up and down the slope until the third operator is satisfied that the bubble is centred. Points A and B are then marked (with stones or pegs). Operator A then moves to B and operator B moves onwards and the process is repeated. This continues until the contour line reaches the far end of the field.
7. Care should be taken that small obstacles, such as minor high spots, or rills, are avoided by skipping forward a pace or two. This avoids sharp irregularities in the contour.
8. When the contour has been laid out, the curves can be smoothed by eye according to the guidelines given for stone or earth bunds.

**Figure A.1 Use of the line level**



### Laying out a graded contour

9. A graded contour deviates slightly from the true contour and is normally used to align a channel, such as a diversion ditch, or to stake out a graded earth bund.

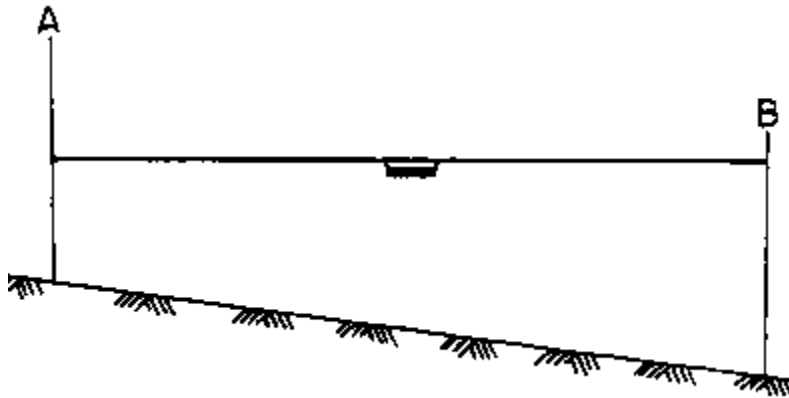
10. In order to lay out a graded contour, further notches must be made on one of the poles. These notches are made below the original notch at intervals of 2 cm.

11. The usual gradient for a structure such as a diversion ditch is 0.25%. The string of the near side operator (A) should be affixed to the second notch down his pole (2 cm below the original) and the far operator (B) retains his string at the original notch. When the bubble in the level is between the two marks, this now implies that A is 2 cm above B, which is equivalent to a 0.25% slope over the distance of 8 metres. For a slope of 0.5%, Operator A fixes his string to the third notch down his pole (4 cm below the top notch) and, when Operator B finds a position where the level reads dead centre, he is at a ground level 4 cm below that of Operator A. Over a distance of 8 metres the slope is then 0.5%.

12. The operation now proceeds as before, operator A moving forward to the spot occupied by B, and B moving onwards - slightly downslope. Once again minor irregularities should be avoided and the curve smoothed.

13. If a diversion ditch must follow a precise field boundary it can be excavated so that the bottom of the ditch is given a suitable gradient. Surveying will therefore take place during excavation.

**Figure A.2. Measuring the slope with a line level**



### Measuring the slope of the land

14. It is simple to use the line level to measure the slope of the land. Operator A stands exactly upslope of Operator B and adjusts the string to the notch which gives a level reading. For example if this notch is the 3rd (i.e. 4 cm below the top notch) the gradient is 0.5%, if the notch is the eleventh (i.e. 20 cm below the top notch) the gradient is 2.5%, etc.

15. Up to 21 notches should be marked on pole A and the following table shows the percentage slope indicated by each.

Notch on Pole A	% slope
Top	0 (level)
2nd (2 cm below top)	0.25
3rd (4 cm below top)	0.50
4th (6 cm below top)	0.75
5th (8 cm below top)	1.00
7th (12 cm below top)	1.50
11th (20 cm below top)	2.50
21st (40 cm below top)	5.00

### Important points to remember

16. Always check the spirit level - by placing it on a horizontal surface and noting the position of the bubble which should be between the two marks.

17. Check the centre point of the string each day and its length also,

18. Remember that when laying out a gradient that operator (A) is upslope.

19. Make sure poles are held vertically.

20. Avoid placing the poles in depressions or on top of minor high spots in the field.

## **A.2 Use of the water tube level for surveying**

### **Introduction**

1. The water tube level is straightforward to use, and farmers can be quickly taught to layout contours. The concept itself - of matching up levels of water - is especially easy to understand. Advantages of the water tube level are that it can be operated by only two people and is more sensitive than the line level on very low slopes. It is, however, slightly less portable than the line level, and is not so simple to use for determining slopes or laying out graded contours.

2. The components of the water tube level are as follows:

- A length of transparent plastic tubing, 6-10 mm inside diameter and about 14 metres long.

- Two poles or staves of about 2 metres in length.

- Four rubber straps (easily made from a bicycle inner tube) to attach the plastic tubing to the poles.

- One to two litres of water. Muddy water is preferable as it is more easily visible in the tube.

3. The plastic tubing is firmly attached to the poles or staves using the rubber straps, or other securing devices. The ends of the tube should be about 10 cm from the top of each staff and the bottom fixing point about 20 cm from the bottom of each staff.

4. The tube is then filled with muddy water until the water level is about halfway up each staff. It is essential that no air bubbles are trapped in the tube and, if necessary, they can be removed by tapping with the finger. Wherever the two staves are set, the free water surfaces in each tube will be at the same level.

### **Laying out a contour**

5. The two staves are placed back to back at the starting point, marked with a peg (A). After any air bubbles have been removed and the water has come to rest, a mark is made on both staves, indicating the water level.

6. The lead man takes one staff and drags the tube in what seems to be the direction of the contour line. When the tube is almost stretched, the lead man moves slowly up and down the slope until his staff is at a position where the water level in the tube coincides with the mark. The staff is then at a position where the ground level's the same as at peg A. A second peg (B) is placed at this point. The back man now moves from peg A to the other side of peg B where the lead man remains stationary. It is now the back man's turn to find the correct spot which is marked by peg C. This procedure continues until the end of the field.

7. The operators then measure, or pace, the horizontal distance required between the contours and begin to lay out the second contour.

8. The contour may then be "smoothed" by eye, according to the design specifications.

### **Important Points to Remember**

9. Work should be carried out during the coolest time of the day because heat causes the plastic tube to stretch and this affects the water levels, which may have to be re-marked.

10. It is important to avoid spillage of water, or the water levels will need re-marking. Water is usually spilled during movement of the staves and this can be avoided by closing the ends of the tube with plugs during movement. It is, however, essential to remove the plugs while making measurements.

11. The poles or staves should always be held vertically.

12. Minor depressions or isolated high spots in the field should be avoided.

## Annotated bibliography

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