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Training manual on agricultural water management

International Water Management Institute

ILRI
INTERNATIONAL LIVESTOCK RESEARCH INSTITUTE

Training manual on agricultural water management

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Supported through:

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Foreword

This set of modules on agricultural water management (AWM), covering five components, is prepared with the aim of providing reference and guide material on smallholders' agricultural water management primarily for Ethiopian farmers through the support of development agents and technical personnel. The materials covered include:

- Module 1: Watershed hydrology for improved agricultural water management
- Module 2: Water harvesting and development for improving productivity
- Module 3: Soil–water–plant relationship
- Module 4: Pumps for small-scale irrigation
- Module 5: Irrigation methods: Part I: Surface irrigation—Options for smallholders; Part II: Drip irrigation—Options for smallholders

The aim of the set of modules is to cover useful elements of AWM from estimating runoff at micro and small watershed level up to irrigated field water management. The modules thus aim at covering water availability estimation, water control and management, soil–water–plant relationship, water lifting and conveyance and irrigation methods. Each module is divided into a number of chapters and illustrated with figures, tables, charts and examples

The modules are also useful as a reference and teaching material at technical, vocational, educational, and training centres and as a field guide.

The documents extensively use existing knowledge in the form of texts, figures, demonstration materials derived from various sources such as books, grey literature such as web material, reports, manuals etc. Specifically they have immensely used materials from FAO, ICRISAT and IWMI documentations with or without citation to the specific references.

We hope that the materials contained in the manuals are useful to enhance management of water and land for improved agricultural productivity.

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Contents

Module 1

Watershed hydrology for improved agricultural water management

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Introduction

Water is the greatest resource to human beings. Socioeconomic development and the civilization of human beings are closely associated to man's ability to utilize and control water resources. Water serves as a positive input for many activities: it meets essential biological needs; it acts as a basic element of social and economic infrastructure; and it serves as a natural amenity contributing to psychological welfare. Water also serves in negative roles such as flooding and diseases transmission. From the earliest days of recorded history, man has recognized the dual nature of water as destroyer and benefactor. Major natural disasters, most notably the Sahelian drought and the loss of tens of thousands of lives as well as coastal and river floods, have brought the subject of water onto the world stage in recent years.

The total amount of water on earth is stupendous, nearly 1400 million cubic kilometers. The impression, which this gives of global superabundance, is misleading, as a major problem is the distribution of water in place and time to meet human needs. The average consumption per person ranges from 20 litres a day in parts of some developing countries to 6000 litres a day in many developed countries. The growing intensity in the utilization of water necessitates the assessment and control of water resources. Better knowledge of the temporal and spatial variations of water supplies is a precondition for the planning, investment and the regulation of systems of water distribution. The basic problem of water distribution in the world is the temporal and spatial difference in the supply and demand of water. The general solution of this problem lies in adjusting water supply and demand so that the demand will always be smaller than or equal to the supply. Storage or harvesting of water is one of the most useful methods for changing the amplitude and phase of the water supply. Such storage or harvesting of water can be carried out only through knowledge of the water resources of the region being considered. The term 'water harvesting' is used to indicate the collection of any kind of water.

The largest use of water in the world is made for irrigating land and more widely for agricultural use. When sufficient and timely water does not become available to crops, the crops fade away, resulting in less crop yields, which can consequently lead to famine and disasters. The planning of available water resources so as to ensure maximum benefits and the design of various irrigation and agricultural water management techniques must be accomplished with fair degree of economy and correctness. For example, evaporation is a decisive element in design of reservoirs to be constructed in arid regions. Crop water requirements and estimation of evaporations from storage and reservoirs are used in determining water supply requirements of proposed agricultural water management projects.

Agricultural water management' (AWM) is now a commonly accepted term to cover a range of technologies and practices whose objective is to ensure that adequate water is available in the root zone of crops when it is needed. It therefore includes capture and storage (in dams, groundwater) as well as drainage of any water used for agriculture (crops, livestock, fish); lifting and transporting water from where it is captured to where it is used for agricultural production or removing excess water from where agriculture is practised; and in in-field applications and water management, including land management practices that affect water availability to crops. (*In-field application and management of water and land is the common denominator*, regardless of the source of the water, and is a critical element of all agriculture). Therefore 'AWM' is critical to successful agricultural production.

Chapter 1 Watershed management

Objectives

After completing this chapter, you will be able to:

- Define and describe watershed
- Carry out a careful field survey
- Estimate and quantify runoff from a given small watershed
- List the problems of a watershed
- Define, document and propose a watershed management plan, programs and analysis
- Understand the different steps of watershed management
- Understand the issues of environmental protection in water resource development
- Appreciate integrated water resource development
- Compare the benefits and costs of watershed management
- Evaluate the results obtained through the management works

What is a watershed?

A watershed is:

- A geographic area where a runoff resulting from drops of rain will be collected and drained through a common confluence point. The confluence point is a single body of water, such as a lake, river or simply a watershed outlet
- A watershed is a catchment or a drainage basin (an area of land within which all waters flow to a single system) of the river system.
- A narrow elevated tract of land separating two drainage basins. A thin line dividing the waters flowing into two different rivers or a divide which separated one watershed from the other.

A watershed can be as small as a basin that drains to a tiny creek, or as large as the Nile River Basin.

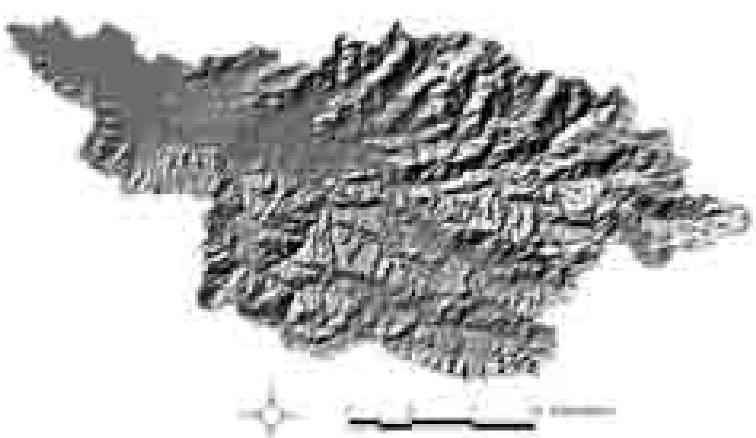


Figure 1. *Example of watershed/catchment of Hare River, Ethiopia (SB Awulachew).*

Watersheds, which are less than 40 ha, are designated as small watersheds while those more than 40 ha are designated as large watersheds.

It is necessary to constantly seek cheaper and more efficient ways of watershed management. The specific land treatment used, as recommended by a soil conservationist, may vary from farm to farm, and even from field to field.

1.1 Principles of watershed management

Watershed management is the process of formulating and carrying out a course of action involving the manipulation of resources in a watershed to provide goods and services without adversely affecting the soil and water base. Usually, watershed management must consider the social, economic and institutional factors operating within and outside the watershed area.

All watersheds contain many kinds of natural resources—soil, water, forest, rangeland, wildlife, minerals etc.

The principles involved in watershed management are summarized below.

1 Carry out careful field survey. Before any work is done, the conservation field men should go out into the field and carefully note the exact lay of the land, the quality of the soil, the degree of erosion damage, and the prevailing erosion hazards on every hectare of every field, wood lot, pasture and idle area of every farm and ranch.

2. Prepare defined documents for watershed management plans and watershed analysis. Watershed management is a treatment of all natural resources in a watershed to protect, maintain and improve water yield. A watershed management plan is a plan for land improvement, rehabilitation of eroded land and human considerations. In the watershed analysis an inventory of all natural resources should be carried out, including a socio-economic bench mark survey, a soil survey, a land use survey, a land capability survey, a vegetation survey, a soil erosion survey and hydrometeorlogical data must be taken. The socio-economic bench mark survey includes an inventory of population, age structure, family size, village organization, education, land tenure, per capita income, farming practices, shifting cultivation, transport systems, marketing facilities, crop yields, fire wood needs, livestock numbers, areas of grazing land, cultivated lands, forage and present livestock feeds.

3. Stress the issue of environmental protection in water resource development. The following actions should be taken as part of environmental policy and impact assessment:
   - Carry out environmental impact assessment
   - Maximize positive environmental impacts and minimize the adverse ones
   - Ensure amelioration measures to reduce environmental problems
   - Control water-borne diseases (such as bilharzias, malaria) and their vectors in irrigated and rain-fed agriculture.

4. Promote integrated water resource development. The 'integrated water resource development' incorporates the issue of environment impact assessment, and social, economic and political aspects of an area. In integrated water resource development, the following activities should be carried out:
   - Evaluate water supply available to the area and describe the places, quantity, quality and characteristics of its occurrence.
   - Estimate the water requirements, both present and future.
   - Estimate potentials of water resource, both present and future.
   - Identify watersheds of water surplus and deficiency.
   - Search possibilities of diverting water from water surplus to water deficient watershed.
   - Propose the best future direction of water resource development.

1.2 Practices of watershed management

Watershed management implies the judicious use of all resources (i.e. land, vegetations and water of the watershed) to achieve maximum production with minimum hazard to the natural resources and for the well being of people and environment. The task of watershed management includes the treatment of land by using the most suitable biological and engineering measures in such a manner that the management work must be economical and socially acceptable. The various factors affecting the task of watershed management are: watershed characteristics (shape and size, topography, relief, and soils); climatic characteristics (precipitation, and amount and intensity of rainfall); watershed operation; land use patterns (vegetative cover, density, and state i.e. type and equality); social status of inhabitants; and water resources and their capabilities.

The major control measures adopted for watershed management works are the vegetative measures or agronomical practices (strip cropping, pasture farming, fertilizing the crop land, grass land farming etc.), and the engineering measures or structural practices (gully control, diversions, water ponds, reservoirs, drainage works, flood protection, ground water recharging structures, terracing, bunding etc.).

1.2.1 Planning of watershed management

The planning of a watershed deals with the watershed description, watershed problems, proposed management programs, effects of interventions, and comparison of benefits and cost.

(A) Watershed description

The description of a watershed should give a clear picture of the watershed's condition by including sufficient information on physical features of the watershed and problems encountered. The factors to be mentioned for watershed description are location, size and shape, climate, geology, slope, surface drainage, physiography, watershed needs, land use and cover conditions, and economic data.

The description of the ***location*** includes the name of river basin tributary, physiographic region, principal communication lines associated, and the latitude and longitude of the watershed. Under the heading ***size and shape***, the size of watershed, either in the unit of km^2 or hectare, and shape of watershed, long and narrow or fan shape should be mentioned. About the ***climate*** of a watershed the following details are collected: precipitation (forms, annual, seasonal and monthly distribution, storm patterns, rainfall intensity, duration and its area distribution), temperature (maximum and minimum, soil temperature etc.), evaporation, relative humidity, wind velocity and its duration, and solar radiation. In the description of the ***geology*** of a watershed, the following geological information should be included: nature of parent rocks, fractures, faults, weathering, ground water recharge and extent of outcrops. The ***slope*** includes the degree of slope, length of slope, mean slope of land surface and proportion of different areas of watershed falling under various slope groups. Regarding the ***surface drainage***, the following information details are required for the description: (a) nature of stream flow, i.e. whether it is perennial, intermittent, ephemeral, spring fed or seasonal, (b) drainage network: stream orders, density and length of streams etc. and (c) morphological characteristics of streams. For describing ***soils*** of a watershed, information details about major soil groups existing in the watershed and their hydrologic grouping, physical and chemical properties of the soils etc. are collected.

The description of the ***physiography*** of a watershed consists of details of elevation of different parts of watershed, mountain ranges etc. Digital elevation models provide good physiographic information. Under the heading ***watershed needs***, contents such as sources of surface and subsurface water (ground water), water use for domestic, irrigation, power generation and recreation purposes, future needs of water exploration etc. are recorded. Under the description of ***land use and cover conditions***, the following details are considered: (a) existing land use and cover condition: forest lands, range lands, cultivated lands, waste lands, habitations, and miscellaneous uses, (b) forests: types and area under each type of forest, hydrologic conditions, legal status, present management, area under regeneration, filling and logging practices, and rights and forest fires, (c) range lands: extent and their major classification, closure, grazing practices, grazing incidence, cattle population (number and types), important grass species, their distribution and hydrological conditions, (d) agricultural lands: extent, land use capability classification, area under each class and subclass, major crops, rain fed areas with suitable crops grown, and orchards and their area. The ***economics*** and ***social data*** are needed to determine the cost–benefit ratio of the project formulated for watershed management. The data to be collected for this purpose are: the economic condition of the population, profession and dependence on resources, market and marketing practices, and return from various resources e.g. from forests, range lands, agricultural lands including irrigated as well as rain-fed.

(B) Watershed problems

The major watershed problems in developing countries are flood, sediment, erosion damage, water management problems and other special problems caused by various factors such as climate variability, deforestation, over population etc. To describe the ***flood damage***, information on amount and value of land exposed to the flood hazards in the watershed; frequency of flood occurrence; significance of small frequent flood or large infrequent flood in total flood problems; limitations; and other pertinent problems are considered.

The problem of ***sediment damage*** is considered in the context of the following cases: reservoir sedimentation, channel silting, drainage, irrigation development, and loss of agricultural land.

The problem of ***erosion damage*** is studied under the following contents: extent of sheet erosion; gully and channel erosion; down stream damage due to sediment deposition; effects on agricultural production due to erosion; and general effects on watershed's economy. ***Water management problem*** includes details on irrigation needs, drainage, water supply required for agricultural and non-agricultural uses and other management needs. ***Special problems*** include landslide, torrents, highway erosion, mines etc.

(C) Proposed management programs

Under this section, the proposed management programs for agricultural lands, irrigation, drainage, flood protection, forest lands, grazing lands, and some special problems are described.

(D) Effects of work

Under this section, the benefits likely to be obtained from various means under watershed management work are estimated and effects of different works of improvement are evaluated.

(E) Comparison of benefits and cost

Computing the average annual benefit and average annual cost of the project makes the comparison of various benefits obtained and cost incurred. The ratio of benefit to cost is computed to show the comparison between them.

1.2.2 Steps of watershed management

The steps of watershed management can be classified into recognition, restoration, protection, and improvement phases. In the recognition phase, watershed problems, their probable causes and development of alternatives for them are identified by conducting several surveys including soil, land capability, agronomic, forest lands under permanent vegetation, engineering, and socio-economic surveys.

The restoration phase covers the selection of best solutions and their applications for watershed management. In this phase, treatment measures (biological and/or engineering measures) are applied to the critical areas of the problems identified earlier during recognition phase, so that these critical areas can be restored to the pre-deterioration stage.

In the protection phase the general health of watershed is taken care of and its normal working is also ensured. In addition to this, the protection of watershed against all those factors, which cause deterioration, is also carried out under this management phase. The protection is preferably made on the critical areas, which are restored in the phase of restoration.

The improvement phase is of paramount importance in watershed management work. Under this phase, the overall improvements made during management of watershed are evaluated for all the lands covered. In addition, attention is also given to make improvement on agricultural land, forest land, forage production, pastureland and socio-economic status of the people.

1.2.3 Evaluation

After the implementation of watershed management measures to overcome the watershed problems or fulfil the objectives of a project, the next step comes in the form of an evaluation of the results obtained. The evaluation of watershed management work should be accomplished under the following two terms:

1 By achievement of management objectives, viz. flood control, sediment control, water supply etc. and
2 Financial returns

Both of these evaluations are necessary for assessing the efficiency of the management work applied to the watershed. It is often observed that the protective benefits safeguard against misery and losses, while the non-quantifiable benefits such as social benefits cannot be easily evaluated in terms of money. Under these circumstances having some financial values to put on them is required. The financial returns are evaluated in terms of benefit–cost ratio, which is determined by accounting all the costs incurred for development work starting from the survey work to the implementation of the programs. The benefit is determined through dividing the entire watershed area kept under different treatments and determining their return in terms of money. The benefit should outweigh the cost.

Economic appraisal of watershed management should include the following basic steps for each alternative:

1. Define and quantify the physical inputs and outputs involved; create tables that show inputs and outputs as they occur over time.

2. Determine unit values (both actual and financial market price and economic values) for inputs and outputs, and estimate likely changes in such values over time, for example, growth in wages or fuel costs.
3. Compare costs and benefits by calculating relevant measures of project worth and other indices and measures needed to answer relevant questions raised by decision makers and also consider the implications of risk and uncertainty.

Chapter 2 Rainfall–runoff relations

Runoff is defined as the portion of the precipitation that makes its ways towards channels, streams, rivers, lakes, oceans etc. as surface or subsurface flow. Based on the time delay between rainfall and runoff, it may be classified into three types: **surface runoff**, **subsurface runoff**, and **base flow (groundwater flow)**. Surface runoff is that portion of rainfall, which enters the stream immediately after rainfall. It occurs when all losses are satisfied and if rain is still continued, with the rate greater than infiltration rate.

2.1 Measurement of runoff from small catchments

Steps:

- Step 1: Select a plot from which runoff is to be collected under controlled conditions.
  - Similar physical characteristics with the water harvesting (WH) scheme planned
  - Minimum size recommended is 3–4 m in width and 10–12 m in length (Figure 2).

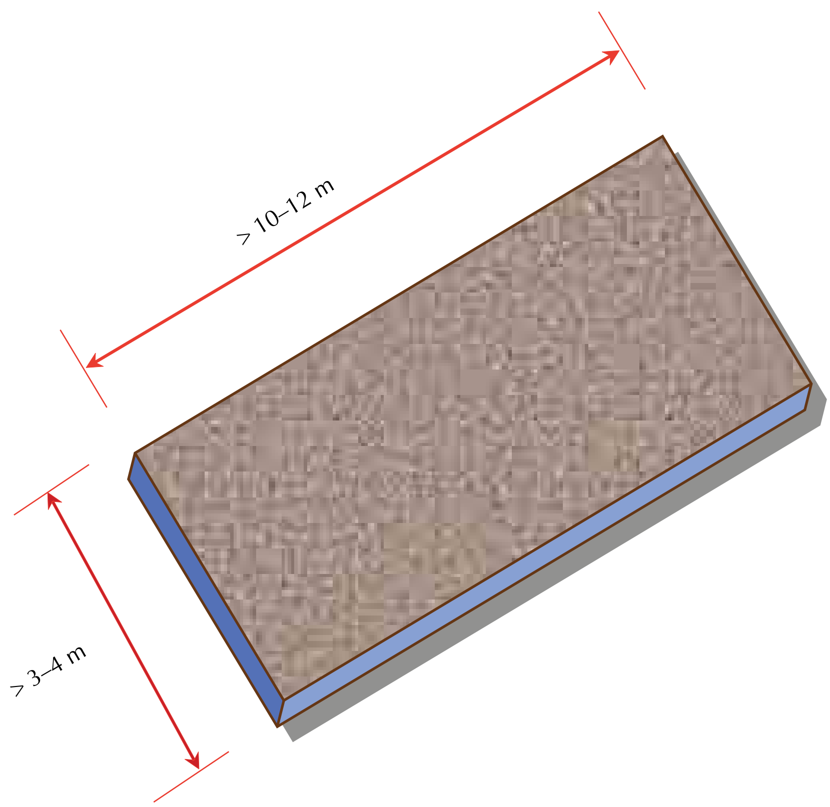


Figure 2. *Dimension of runoff plot for measuring runoff.*

- Step 2: Around the plots metal sheets or wooden planks must be driven into the soil with at least 15 cm of height above the ground. Earth bunds of the same height may be constructed.
- Step 3: Install a rain gauge near the plot, a gutter at the lower end of the plot, and a measuring tank at the lower end of the gutter.
- Step 4: Measure the volume of water collected in the rain gauge and in the runoff tank after every storm (or every day at a specific time).

2.2 Determination of runoff from large catchments

Curve number method

The curve number method:

- Enables determination of runoff coefficient without direct runoff measurement
- Makes use of rainfall depth (P) and curve number or hydrologic soil–cover complex number (CN)
- Mainly useful for large catchments.

Curve number (CN) is a function of:

- Hydrologic soil group
- Land use
- Hydrologic condition
- Antecedent runoff conditions

The following equation is used for estimating runoff:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad (1)$$

Where P is the intensity of rainfall and S is the retention capacity of the watershed. The retention capacity (S) of the watershed can be predicted using the curve number (CN), as defined by U.S. Soil Conservation Service, given as:

$$CN = \frac{25400}{254 + S} \quad \text{(unit in mm)} \quad \text{or} \qquad (2a)$$

$$CN = \frac{2540}{25.4 + S} \quad \text{(unit in cm)} \qquad (2b)$$

Solving for S, it follows that

$$S = \frac{25400}{CN} - 254 \quad \text{(unit in mm)} \qquad (2c)$$

where CN is curve number. Its value varies from minimum zero for most permeable surface to 100 for impervious (concrete) surface. Curve numbers can be obtained from Table 1. These values apply to antecedent rainfall condition II, which is an average value of annual floods. Correction factors for other antecedent rainfall conditions are listed in Table 2. Condition I is for low rainfall potential with soil having low antecedent water content suitable for cultivation. Condition III is for wet conditions prior to the storm.

Table 1. *Runoff curve numbers for hydrologic soil cover complex for antecedent rainfall condition II and initial abstraction Ia = 0.25*

Land use or crop	Treatment or practice	Hydrologic condition	Hydrologic soil group			
			A	B	C	D
Fallow	straight row	–	77	86	91	94
Row crops	straight row	poor	72	81	88	91
	straight row	good	67	78	85	89
	contoured	poor	70	79	84	88
	contoured	good	65	75	82	86
	terraced	poor	66	74	80	82
	terraced	good	62	71	78	81
Small grain	straight row	poor	65	76	84	88
	straight row	good	63	75	83	87
	contoured	poor	63	74	82	85
	contoured	good	61	73	81	84
	terraced	poor	61	72	79	82
	terraced	good	59	70	78	81
Close-seeded legumes or rotation meadow	straight row	poor	66	77	85	89
	straight row	good	58	72	81	85
	contoured	poor	64	75	83	85
	contoured	good	55	69	78	83
	terraced	poor	63	73	80	83
	terraced	good	51	67	76	80
Pasture or range		poor	69	79	86	89
		fair	49	69	79	84
		good	39	61	74	80
	contoured	poor	47	67	81	88
	contoured	fair	25	59	75	83
	contoured	good	6	35	70	79
Meadow (permanent)		good	30	58	71	78
Woods (woodlots)		poor	45	66	77	83
		fair	36	60	73	79
		good	25	55	70	77
Farmsteads		–	59	74	82	86
Roads and right-of-way (hard surface		–	74	84	90	92

Note: I_{fr} = final infiltration rate

Soil group	Description	Ifr (mm/h)
A	Lowest runoff potential. Includes deep sands with very little silt and clay, also deep, rapidly permeable loess.	8–12
B	Moderately low runoff potential. Mostly sandy soils less deep than A, but the group as a whole has above average infiltration after thorough wetting.	4–8
C	Moderately high runoff potential. Comprises shallow soils and soils containing considerable clay and colloids, though less than those of group D. The group has below average infiltration after pre-saturation.	1–4
D	Highest runoff potential. Includes mostly clays of high swelling percent, but the group also includes some shallow soils with nearly impermeable subhorizons near the surface.	0–1

Table 2. *Antecedent rainfall conditions and curve numbers (for Ia = 0.25)*

Curve number for condition II	Factors to convert curve number from condition II to	
	Condition I	Condition III
10	0.40	2.22
20	0.45	1.85
30	0.50	1.67
40	0.55	1.50
50	0.62	1.40
60	0.67	1.30
70	0.73	1.21
80	0.79	1.14
90	0.87	1.07
100	1.00	1.00

Conditions	General description	5-day antecedent rainfall (mm)	
		Dormant season	Growing season
I	Optimum soil condition from about lower plastic limit to wilting point	<13	<36
II	Average value of annual floods	13–28	36–53
III	Heavy rainfall or light rainfall and low temperatures within 5 days prior to the given storm	>28	>53

Example 2.1. A small watershed has a hydrologic soil group D and contoured good pasture cover. The rainfall was recorded as 60 mm. Calculate the direct runoff from the watershed for average condition of soil cover and antecedent moisture.

Solution:

1. Using Table 1, find the value of CN for soil group D and contoured good pasture cover, which is obtained as 79.
2. Find the value of S as:

$$S = \frac{25400}{CN} - 254 = \frac{25400}{79} - 254 = 67.5 \text{ mm}$$

3. Determine the direct runoff as

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} = \frac{(60 - 0.2 \times 67.5)^2}{60 + 0.8 \times 67.5} = 19 \text{ mm}$$

The direct runoff from the watershed is 19 mm.

2.3 Determination of peak discharge

Peak discharge is the maximum amount of runoff (discharge) for which the structures are designed. It can be computed using different methods such as rational method, empirical formulas, unit hydrograph, flood frequency analysis etc. (Table 3)

Table 3. *Computation methods*

Methods	Applicable catchment area
Rational method	< 50 km^2
Empirical formula	
Unit hydrograph	< 5000 km^2
flood frequency analysis	

Rational Formula (method).

$$Qp = \frac{K_r IA}{3.6} \quad (3)$$

Q_p = peak flood discharge (m^3/s)
Kr = rational runoff coefficient
I = rainfall intensity (mm/hr)
A = area of the catchment (km^2)

Rational method: Steps

- Step 1: Compute time of concentration (tc) with the following formula.

$$Tc = \frac{0.019471 \text{ x } L^{0.77}}{S^{0 \cdot 385}} \quad (4)$$

Tc = time of concentration (minutes)
L = maximum length of travel of water (m)
S = slope of the catchment, (= H/L)
H = the difference in elevation between the outlet and remote point.

- Step 2: Find the corresponding intensity (I) for duration equal to Tc for a certain return period, from the Intensity—duration—frequency curve prepared for the area.

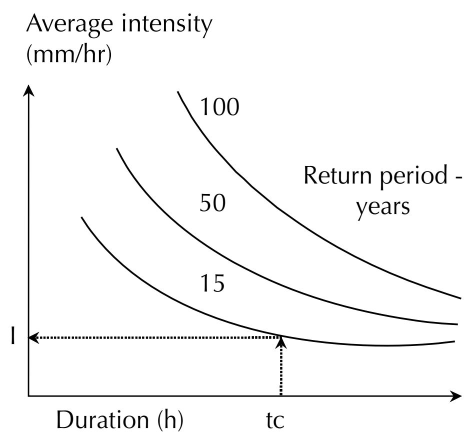


Figure 3. *Intensity–duration–frequency curve (sample).*

- Step 3: Select suitable rational runoff coefficient Kr, having knowledge of the surface cover of the catchment area. Use Table 4.

Table 4. *Values of rational runoff coefficient Kr*

General slope	Land cover	Value of kr
Flat area	Tight clay	
	Cultivated	0.50
	Woodland	0.40
Hilly area	Tight clay	
	Cultivated	0.70
	Woodland	0.60
	Sandy loam	
	Cultivated	0.40
	Woodland	0.30

Step 4: Compute Qp using the rational formula.

$$Qp = \frac{K_r IA}{3.6}$$

2.4 Assessment of rainfall–runoff relations

The rainfall–runoff relations can be assessed using runoff coefficient, graphical correlation or analytical correlation between rainfall and runoff.

Use of runoff coefficient

The runoff coefficient needs to be based on actual, simultaneous measurements of both rainfall and runoff. Runoff coefficients derived for watersheds other than the project area should be avoided. At least 2 years of rainfall and runoff measurements are required to arrive at a representative figure. It ranges usually between 0.1 and 0.5. Yearly or seasonal runoff coefficient can be used.

$$\textit{Runoff} = \textit{Runoff coefficient} \times \textit{rainfall} \tag{5}$$

Graphical correlation between rainfall and runoff

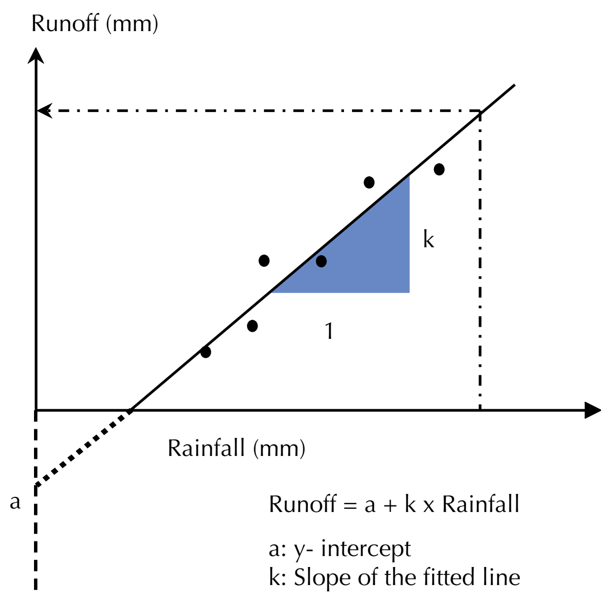


Figure 4. *Graphical correlation between rainfall and runoff.*

Analytical correlation between rainfall and runoff

$$R = a + k \times P$$

$$k = \frac{N(\sum P \times R) - (\sum P) \times (\sum R)}{N(\sum P^2) - (\sum P^2)}$$

$$a = \frac{\sum R - K \sum P}{N}$$

$$r = \frac{N(\sum R \times P) - (\sum P) \times (\sum R)}{\sqrt{\{[N(\sum P)^2 - (\sum P)^2] - [N(\sum R)^2 - (\sum R)^2]\}}}$$

R = Run off (mm)

P = Rainfall (mm)

N = Number of sets of P and R

R = Coefficient of correlation ($0 < r < 1$)

a & k = constants

Chapter 3 Required storage capacity and yield

3.1 Required storage capacity

The capacity of a reservoir is determined from a contour map of the reservoir site. The area enclosed within each contour is measured with a planimeter. The incremental volume ΔV of water stored between any two successive contours can be determined using one of the following equations:

$$\Delta V = \frac{h}{2}(A_1 + A_2) \qquad \text{Trapezoidal formula} \tag{6}$$

$$V = \frac{h}{3}(A_1 + A_2 + \sqrt{A_1 A_2}) \qquad \text{Cone formula} \tag{7}$$

$$V = \frac{h}{6}(A_1 + 4A_2 + A_2) \qquad \text{Prismoidal formula} \tag{8}$$

Where A_1 and A_2 are the areas corresponding to two successive contour values and h is the elevation difference between them. Then *area-elevation* and *storage-elevation* curves are plotted. The required storage capacity is determined from water demand and losses (Figure 5).

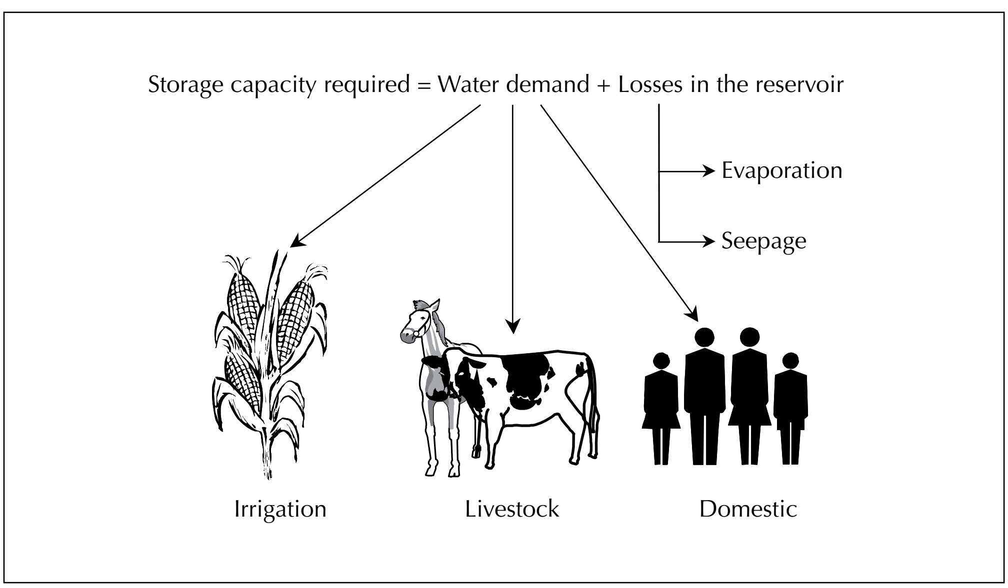


Figure 5. *Water demand and losses.*

3.1.1 Irrigation water demand

$$Ir\,(m^3) = \frac{10 \times ET_{crop}(mm) \times Ca\,(ha)}{Ef} \tag{9}$$

where

Ir = Irrigation water requirements in cubic metres for the whole dry period

ETcrop = Crop water requirement in mm during the dry period
Ca = Area irrigated with water from the reservoir in ha
Ef = Overall water application efficiency

Crop water requirement, ET_{crop}

$$ETcrop = Kc \times ETo \tag{10}$$

where

ETcrop = Crop water requirement in mm per unit of time
Kc = Crop factor (crop coefficient)
ETo = Reference crop evapotranspiration in mm per unit time

Computation of ETo

Table 5. *Minimum data requirement for various ETo computation methods*

Method	Temp.	Humid.	Wind	Sunsh.	Rad.	Evap.	Env.
Blaney-criddle	M	E	E	E			E
Radiation	M	E	E	M	(M)		E
Penman	M	M	M	M	(M)		E
Pan		E	E			M	M

Class A evaporation pan: measurement of Epan

- 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 certain period of time (usually 24 hours)
- measurement is usually taken at 7:00 hours
- rainfall, if any, is measured simultaneously
- the difference between the two measured water depths yields the pan evaporation rate: Epan (mm/24 hours)

The pan has 121 cm diameter and 25 cm depth.

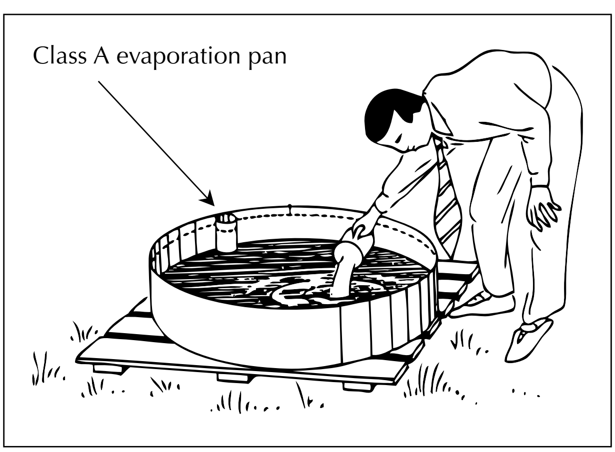


Figure 6. *Class A evaporation pan.*

Pan Evaporation method

$$ETo = Epan \times Kpan \tag{11}$$

Epan = Evaporation from pan (standard pan is Class A pan)

Kpan = Pan factor. It varies between 0.35 and 0.85. Average value is 0.7

Blaney-Criddle method

$$ETo = p\,(0.46\,Tmean + 8) \qquad (12)$$

Tmean = Mean daily temperature (ºC)

p = mean daily percentage of annual day time hours

Table 6. *Indicative values of ETo*

Climatic zone	Mean daily temperature		
	Low (<15ºC)	Medium (15–25ºC)	High (>25ºC)
Arid	4–6 mm/d	7–8 mm/d	9–10 mm/d
Semi-arid	4–5 mm/d	6–7 mm/d	8–9 mm/d

Crop factor (Kc)

- Varies for different crops
- Varies with growing stages
- Varies in climate

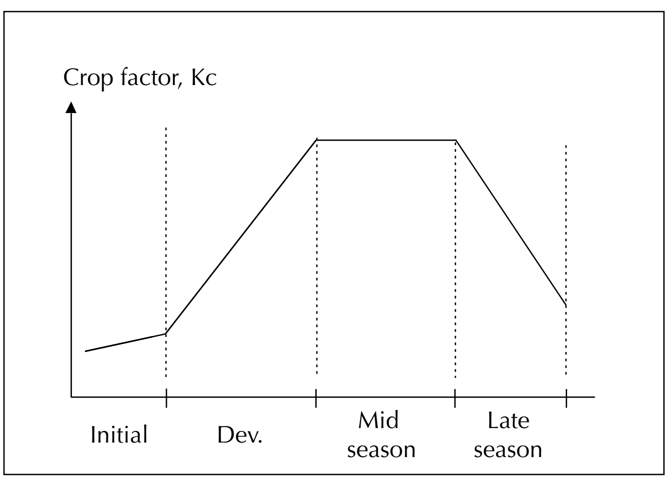


Figure 7. *Variation of Kc in growing stages.*

Crop factor (Kc)

Table 7. *Crop factors for the most commonly grown crops under WH*

Crop	Initial stage	Days	Crop	Days	Mid-season stage	Days	Days	Season average
Cotton	0.45	30	0.75	50	1.15	55	45	0.82
Maize	0.40	20	0.80	35	1.15	40	30	0.83
Millet	0.35	15	0.70	25	1.10	40	25	0.79
Sorghum	0.35	20	0.75	30	1.10	40	30	0.78
Grain/small	0.35	20	0.75	30	1.10	60	40	0.78
Legumes	0.45	15	0.75	25	1.10	35	15	0.80
Groundnuts	0.45	25	0.75	35	1.05	45	25	0.79

Adapted from Critchley and Siegert (1991).

3.1.2 Water demand for livestock

$$W_L = \frac{N_L A_c T}{1000} \qquad (13)$$

W_L = Water needed for livestock during the whole dry period in cubic metres
N_L = Number of animals to be watered from the reservoir
Ac = Average rate of animal water consumption in litres/day per animal 25–60 litre/animal per day
T = Duration of the dry period in days

Table 8. *Average daily water consumption of selected animals*

Animal	Consumption (litre/day)
Camel	50
Cattle	27
Sheep	5
Goat	5
Donkey	16

3.1.3 Water demand for domestic use

$$W_d = \frac{P_o D_c T}{1000} \qquad (14)$$

W_d = Domestic water supply during the dry period in cubic metres
P_o = Users of the reservoir
D_c = Average rate of water consumption in litres per day per person (40 litres/person per day)
T = Duration of the dry period in days

3.1.4 Losses due to evaporation and seepage

Evaporation losses:

- Can be calculated or measured using Pan A

Seepage losses:

- Difficult to assess as it depends on permeability of the prevailing soil
- As a rule of thumb can be assumed equal to ETo losses

Total losses = Evaporation loss + Seepage loss (15)

3.2 Assessment of safe yield

A *reservoir yield* is the amount of water that can be drawn from the reservoir in a certain interval of time. The time interval may vary from a day for small distribution reservoirs to a month or a year for larger reservoirs. Yield is dependent upon inflow and varies from time to time. The maximum quantity of water that can be supplied from a reservoir with a full guarantee during worst dry (critical) periods is known as the *safe* or *firm yield*. Water available in excess of the safe yield during periods of high flows is known as *secondary yield*. The arithmetic average of safe and secondary yields over a long period of time is called *average yield*.

The yield of a reservoir and its storage capacity are very much dependent upon each other. Capacity of a reservoir depends upon the demand (i.e. yield). If more water is required, more capacity has to be provided. The capacity and yield (i.e. outflow) are governed by the storage equation given by:

$$\text{Inflow} - \text{Outflow} = \text{Increase in storage}$$
$$\text{Yield (Outflow)} = \text{Inflow} - \text{Increase in storage} \tag{16}$$

- Assessment of annual safe yield:
  - Get annual runoff or rainfall amount
  - Make frequency analysis

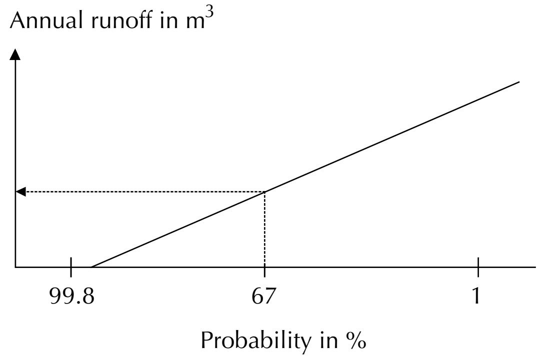


Figure 8. *Probability analysis of runoff.*

Chapter 4 Slope stabilization

Slope stabilization considers the use of vegetation (soil bioengineering) and slope stability structures (biotechnical engineering) for slope protection. When properly installed and maintained, vegetation can protect slopes by reducing erosion, strengthening soil, and inhibiting landslides, which increase general slope stability. The use of vegetation to manage erosion and protect slopes is relatively inexpensive, does not require heavy machinery on the slope, establishes wildlife habitat, and can improve the aesthetic quality of the property.

4.1 Planting program

The planting program shall consider *planting zones*, *slope crest*, *slope face*, *slope toe*, *planting times*, and *maintenance*. Without using more advanced stabilization techniques, the maximum slope to be considered for vegetative stabilization is 1.5 horizontal to 1 vertical (1.5H:1V). There are many good plants in the form of grasses, vines, shrubs, and minor trees that can be used for slope stabilization projects. Plant selection is dependent upon the goals of your erosion control program and site conditions. Typically, effective programs incorporate structural diversity in plant selections (trees/shrubs with ground covers) and use a mix of species.

Vegetation should be established on patchy and barren slope faces or terraces to reduce erosion. Planting practicality depends greatly on the character of the slope, and particularly on the slope angle. A slope of 1.5H:1V (33 degrees) should be considered as the dividing line between a manageable slope and a slope steep enough that vegetation would be difficult or impossible to establish without employing other reinforcement techniques. If room exists at the top of a slope, low slopes can be graded back to a gentler configuration. Various species and mixtures of species can be planted on slope faces and expected to succeed in this rather severe environment. These include seed mixtures of grasses and legumes and a range of shrubs and minor trees. Large trees should be used on the face of slopes sparingly and with caution. Should these trees collapse because of the undermining of the root system by erosion or by wind throw, the tree roots can disturb large volumes of earth when they pull from the slope. The resulting large, bare areas are opened to further erosion, which may endanger adjacent land and vegetation. New major trees should not generally be established on the face of coastal slopes. Existing major trees should be closely monitored for signs of undercutting and toppling. If the trees become unstable, they should be cut before they fall. Root systems should be left intact to bind the soil for a short period of time while new live, well-rooted vegetation establishes itself. Establishing new vegetation prior to felling a tree would be advantageous to the slope protection program.

In those situations where the bottom of your slope is susceptible to frequent or periodic wave attack, vegetation alone will not be adequate as an erosion control tool. In such cases a form of structural toe protection may also be required. If the toe is not subject to coastal marine erosive forces, trees and woody shrubs can be useful in resisting upland land sliding and tolerating the dynamic changes in the coastal shore system.

You should plan for maintenance considerations in your erosion control program. Most programs do not have significant long-term maintenance requirements.

4.2. Planting techniques

There are six general planting techniques: (1) seeding, (2) container or bare root, (3) live staking, (4) contour wattling, (5) biotechnical solutions and (6) brush layering.

4.2.1. Seeding

Seeding involves the application of grass and woody plant seed mixes to slope areas. Seeds may be applied to slopes by broadcasting seed mixes onto the slope by hand or by placing seed into small holes placed into the slope. Hydro-seeding is also another option used for hard-to-access locations. Seeding creates a shallow fibrous rooting zone in the upper foot or on the surface profile, which binds near-surface soils and protects soil surfaces from surface water runoff, wind, and freeze-thaw erosive forces. Seeding is usually applied in combination with other planting techniques to address most erosion control issues.

Drilling soil holes into the slope area can reduce the seed quantities required. Practically, this method is best used on mild slopes, in smaller prescription areas, and for woody plant seed stock, which is more expensive than grass seed mixes. Typically, a 7.5 cm diameter by a 10 cm deep hole is a good size for the planting hole. Make sure the surrounding soil is loosened around the hole so that future root systems can develop. Drop a slow release fertilizer capsule to the bottom of the hole and cover with about 8 cm of soil. Then place about 20 seeds into the hole and cover the seed as directed by the seed supplier.

Broadcast seeding is the most common application method employed in projects. Seeds are scattered uniformly by hand onto the slope. If the application area soil has been roughened slightly, seed germination will be more successful. It is also important to make sure precipitation does not wash seeds down the slope. Mulch seed immediately to keep seeds from being blown and washed away, or be eaten by wildlife, and to keep the surface soils moist. Fertilize areas as required by mix directions. Hydro-seeding is another application method that uses seed mixed with water, fertilizer, and sometimes mulches to spray the mixture onto expansive or hard to reach slope areas.

4.2.2. Container or bare root planting

Container and bare root planting involves placing single or bunches of rooted plants into excavated holes on the slope. This method can be used for woody plants or for non-woody plants, which will eventually spread into uniform root coverage. Container and bare root plant material can be purchased directly from nurseries or gathered from other sites and propagated by the landowner.

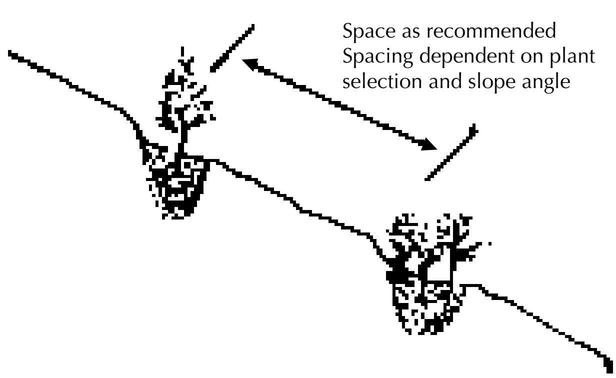


Figure 9. *Container/bare root planting (single or bunch planting).*

Because the immediate slope stabilization expectations of using rooted materials are often too high, it is a good idea to use plant groupings or bunch plantings. This method allows you to place plants, which have slightly different rooting and foliage characteristics, which may strengthen the overall

4.2.3. Live staking

Live stakes are sections of woody plants that are cut into lengths and placed into the slope. The plant material is installed during the fall or spring when the original plants are dormant. The plant materials used for stakes are usually hardy species which root easily and eventually grow into mature woody shrubs that reinforce the soil structure of the slope.

Woody plants, which have good rooting characteristics, make good staking plant stock. Stakes are generally 60 to 90 cm long and 1 to 2.5 cm in diameter and can be collected from sections or branches of plants from donor sites. Stakes should be flat cut on the top and diagonal cut on the bottom so they will be installed correctly.

Staking can be used alone or with other planting techniques. Typically, if stakes are used alone on the slope they will be spaced across the slope as recommended for each species and slope situation. Each row should have the same spacing but should alternate stake positions so that if you look down or up slope no two consecutive rows should have stakes directly above or below one another (a diamond pattern). Stake rooting will be most effective if the stake is not positioned vertically but positioned at an angle off horizontal so that rooting can occur more effectively along the entire below ground length as shown on Figure 10.

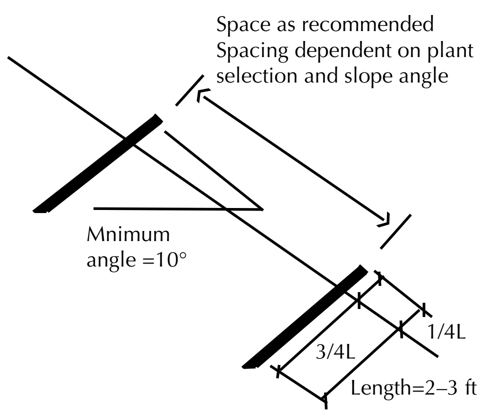


Figure 10. *Live staking.*

Stakes are typically being placed into predrilled holes using rebar sections, which are slightly smaller than the diameter of the stakes. Gently tap stakes into holes with soft mallets or other instruments. Remove the top section of the stakes that get damaged during installation. It is good practice to mulch the staked area after the installation is completed.

Live staking is also used with contour wattling to secure wattles along a contour. The method of stake installation is the same as described for independent stakes.

4.2.4. Contour wattling

Contour wattling is an erosion control planting method, which can also be used to stabilize very shallow soil structure against land sliding. The method involves packing lengths of woody plant material into cables or bundles (sometimes called live fascines) about 20 to 25 cm in diameter.

The bundles are laid continuously along slope contours as shown in Figure 11. The cabling effect along the slope helps to intercept surface water runoff and route it laterally before it creates erosion problems. The wattles help trap sediment by creating barriers (living fences) to protect down slope areas against material falls or erosion.

1) Excavate small trench along slope contour. Place live stakes along trench edge on 3-foot centres (see section on live stakes)
2) Place wattles into trench with ends overlapping. Secure dead stakes through middle of wattles at 2–3 foot centres
3) Pull excavated soil down into and around wattles leaving approximately 20% of wattle area located above slope surface yet in contact with the soil. Walk on wattles to compact and achieve good soil-wattle contact
4) Move upslope to next trench alignment and repeat process

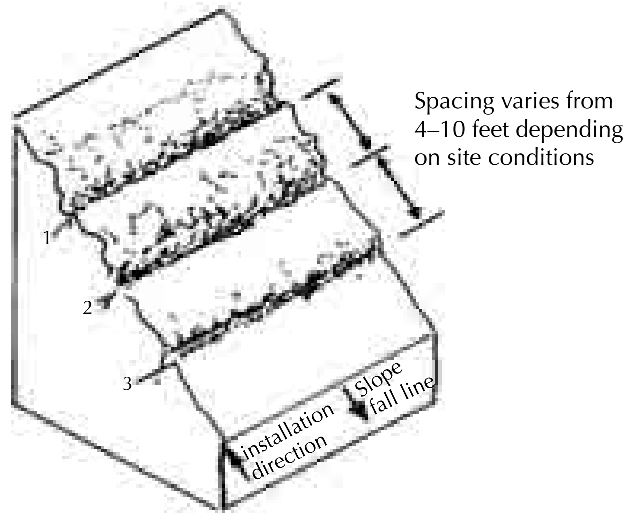


Figure 11. *Contour wattling.*

Wattling is generally considered good for slopes of 1.5H:1V or less. The installation of wattles along slopes requires a greater degree of planning prior to installation. Generally, wattles are placed horizontally in shallow trenches along pre-selected alignments on the slope at a single contour elevation. The wattles are placed into the trenches and partially covered creating what appear like slope terraces. Wattling installation along a slope face should progress from the slope toe upslope to the crest until planting is complete.

Wattles can be created by laying plant materials length wise between two bucking horses (or modified saw-horses). Plant materials should be about 1–3.5 cm in diameter and about 1.2 to 2.4 metres in length. Butt ends and top ends are usually laid alternately until a bundle has been created that looks like 20 to 25 cm wide cigar. Bundles are then tied together using untreated lengths of twine (Figure 12). This process is repeated until you fabricated the length of wattling necessary to finish a contour length. Next you live stake the down slope side of the trenches to hold the wattles in the trench overlapping the ends of bundles slightly. Place dead stakes (60 cm long) through the wattles every 60 cm. Finally, pull the soil from the trench excavation down into the wattles and compact into the trench by walking on the bundles. Make sure there is good soil–plant contact around and in the wattle.

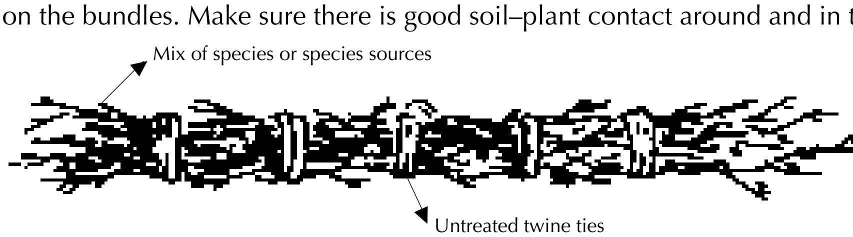


Figure 12. *Wattle detail.*

About 80% of the wattle should be buried below the existing soil surface as shown in Figure 13. Leave the remaining area above the existing soil surface, then cover with soil to intercept water and create mild slope terraces. At this time it is good to excavate the next upslope trench and then repeat the process. It is important to get the plant materials into the trenches before they have a chance to lose critical stem moisture. Seeding and mulching should follow immediately after installation.

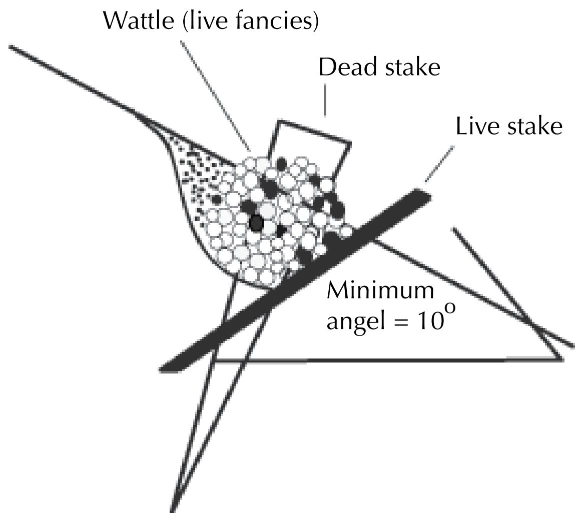


Figure 13. *Contour wattling detail.*

4.2.5. Biotechnical solutions

Although biotechnical solution (avoidance or retreat) is not truly a planting procedure, it should be discussed as a viable technique to consider when it comes to slope restoration using geotechnical engineering design and stability construction. For some sites, it will be more economical for homeowners to relocate structures away from slope crests than to mobilize construction crews to perform traditional advanced geotechnical slope stabilization. If structures can be relocated, greenbelts and low-impact slope planting may proceed with less risk to structures. Biotechnical engineering solutions use both vegetation and inert structural designs to address steep slopes greater than 1.5H:1V, known landslide areas, complicated drainage issues, and slope restoration programs

4.2.6. Brush layering

Brush layer planting consists of live woody plant material placed into the slope face along trenches excavated along slope contours as shown in Figure 15. This technique is most applicable to areas subjected to cut or fill operations or areas that are highly disturbed and/or eroded. Layering provides the best technique to achieve soil reinforcement to resist potential shallow-seated land sliding events. Brush layers act as live fences to capture debris moving down the slope. Figure 14 illustrates the proper steps to take when implementing the brush layering technique.

1) Excavate trench so that approximately 1/4 of average brush length extends beyong slope face. Do not over excavate.
2) Lay an appropriate mix of brush species and/or brush species from different sources along trench sidewall.
3) Pull excavated soil down into trench and compact soil into the original shape configuration. Slightly mound soil behind brush layers.
4) Move upslope to next trench alignments and repeat process.

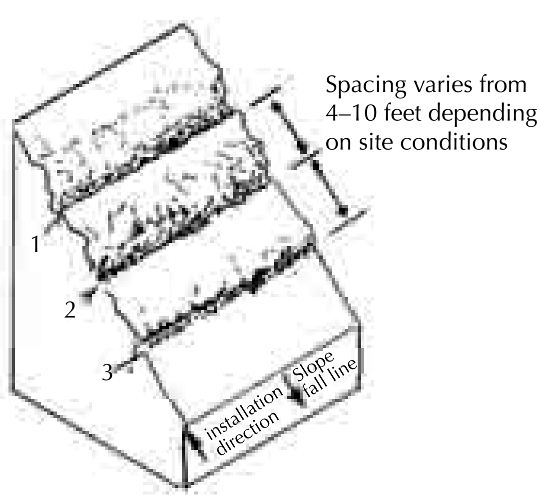


Figure 14. *Brush layering.*

This technique can be very disruptive to native soils and can trigger soil movements during installation. It is important to perform installation in phases and not to excavate more area than is necessary to install plant materials.

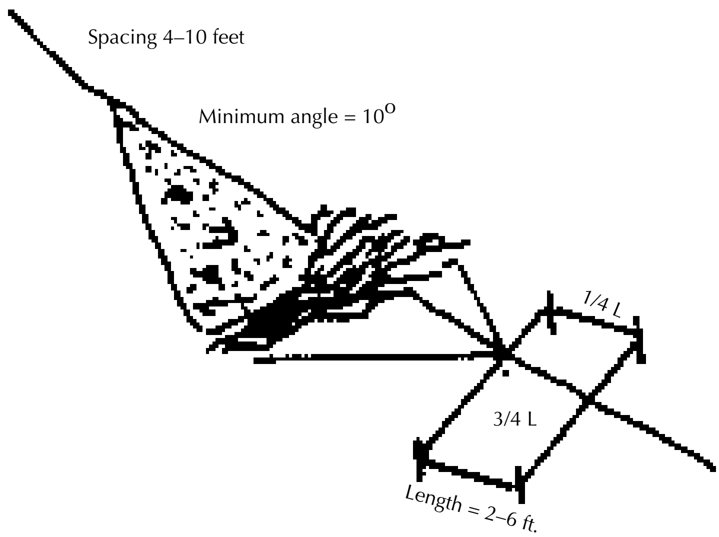


Figure 15. *Brush layering detail.*

If there are large quantities of loosened soils on the slope, layering is a good slope stabilization approach. Also, if imported soil material will be used to restore eroded areas, brush layering should be considered. It is best to install materials into the imported fill area and avoid disturbing existing soil structures. Use brush layering on slopes up to 1.5H:1V or in highly eroded gully areas (Figure 15). Plant material should be prepared as described under contour wattling except for the length of the collected material.

Limitations

Not good for dense, stiff soil structures. Not recommended as a solution to gully erosion control unless technique shown on Figure 16 is used to rehabilitate gullies.

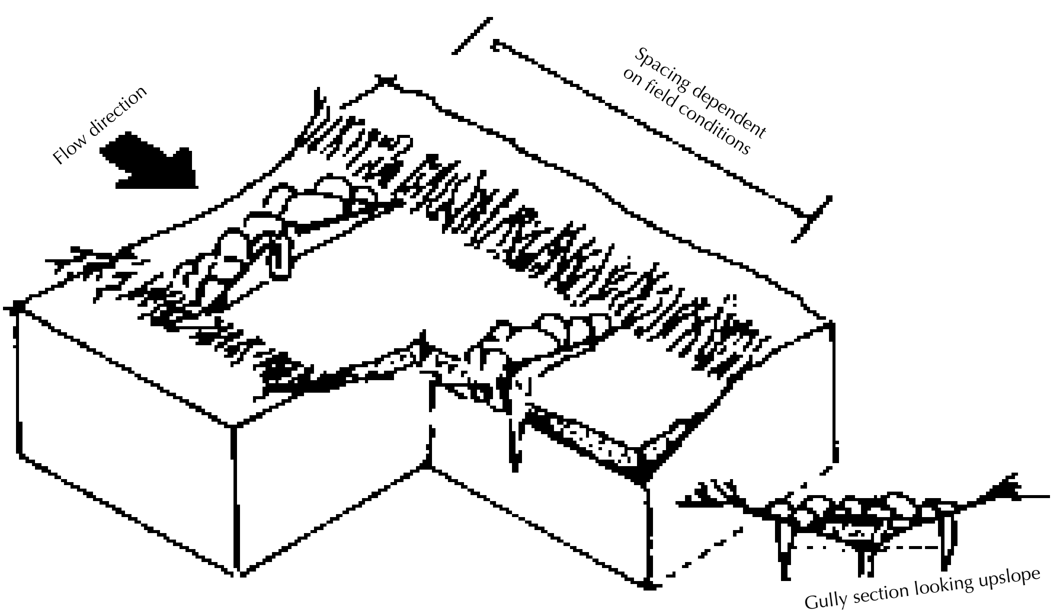


Figure 16. *Brush layering for gullies.*

Chapter 5 Bunding

Bunding is an engineering conservation measure used for retaining water, creating obstruction and thus to control erosion. Bunds are simply embankment-like structures, constructed across the land slope. They are called contour bund, if they are constructed on the contour of the area, and graded bund, if they are provided some horizontal grade. The main objectives of contour bunding are to cut longer slopes into series of smaller slopes to increase time of concentration, to increase infiltration rate, to decrease velocity of runoff and as a result to protect soil against erosion.

Very shallow soils and very deep black clay soils are not suitable for bunding. Very shallow soils do not have enough earth for building bunds (Table 9). Very deep black clay soils expand easily on wetting and contract on drying forming cracks on bunds. Bunding are used on land slopes of 2 to 10%.

Table 9. *Soils suitable for bunding*

Soil	Depth (cm)
Very shallow	Less than 25
Shallow	25 to 50
Medium depth	50 to 90
Deep	90 to 150
Very deep	more than 150

The bunding systems are divided according to the function which they perform, as:

- Contour bunding (narrow based or broad based), and
- Graded bunding (narrow based or broad based)

5.1 Spacing of bunds

The following formula can be used to determine the spacing of bunds:

$$V.I. = \frac{S}{a} + b \qquad (17)$$

Where VI is vertical interval between two successive bunds, S is land slope in percent, and a and b are constants depending upon soil and rainfall characteristics of the area. The above equation can be modified for the specific areas having different rainfall amounts. For the areas of heavy rainfall, it follows that

$$VI = \frac{S}{10} + 0.6 \qquad (18)$$

And for areas having low rainfall

$$VI = \frac{3S}{20} + 0.6 \qquad (19)$$

The formula which was developed for the subhumid climate of the United State is

$$VI = \frac{S}{10} + 0.6 \qquad (20)$$

Infiltration and rainfall affect the spacing of bunds. The effects of these factors are incorporated in the following equation:

$$VI = 0.3\ (XS + Y) \qquad (21)$$

in which, VI is vertical interval in metre, X is the rainfall factor, Y is infiltration and crop cover factor and S is percent land slope. The X and Y values are given in Tables 10 and 11, respectively.

Table 10. *Values of rainfall factor (X)*

Rainfall distribution	Annual rainfall mm)	X
Scanty	< 640	0.80
Moderate	640–900	0.60
Heavy	> 900	0.40

Table 11. *Values of Y based on intake rate and crop cover*

Intake rate	Crop cover during Erosive period of rain	Y
Scanty	Low coverage	1.0
Moderate	Good coverage	2.0
One of the above factors favourable and the other unfavourable		1.5

Example 5.1. On an area having moderate rainfall distribution, average intake rate and good crop cover during erosive period of rainfall, a bund is going to be constructed. If the annual amount of rainfall is 800 mm and the land slope is 5%, calculate the vertical interval to be used in the bund construction.

Solution

Given S = 5%, X = 0.60 (from Table 10), and Y = 2.0 (from Table 11). Therefore

$$VI = 0.3(XS + Y)$$
$$= 0.3\ (0.6 \times 5 + 2) = 1.5 \text{ m}$$

5.2 Size of bunds

The size of a bund includes its height, top width, side slopes and bottom width. The height of a bund is first determined and then the other factors can be easily obtained. The height of the bund is determined on the basis of the amount of water to be intercepted by the bund. It can be determined from the equation

$$h = \sqrt{\frac{3.x.S}{1000}} \qquad (22)$$

in which, h is the height of the bund, x is the horizontal distance between two successive bunds, and S percent land slope. Settlement allowance of about 5% and a free board of 30 to 50 cm should be added to the calculated height.

5.3 Side slope of bunds

The side slope of a bund is dependent on internal frictional angle of the fill material. Recommended values of side slopes are given in Table 12. From the height and the side slope of a bund, its top and bottom widths can be determined.

Table 12. *Recommended bund side slopes for different soil types*

SN	Soil type	Side slope (H:V)
1	Red gravel, light red loam, black loam, white gravel	1.5:1
2	Light sandy loam, clay, black cotton soil, decomposed rock	2:1
3	Sand	2.5:1

5.4 Length and earthwork of bunds

The length of bund per hectare area of land is calculated using the equation:

$$L = \frac{10000}{HI} = \frac{10000 \times S}{VI \times 100} = 100\,\frac{S}{VI} \qquad (23)$$

The earthwork of bunding system includes the sum of earthworks made in main contour bunds, side bunds and lateral bunds formed in the field. The earthwork of any bund is obtained by multiplying the cross sectional area to its total length. The total earthwork can be given by the following equation.

$$E_t = E_m + E_s + E_l \qquad (24)$$

where, E_t = total earth work,
E_m = earthwork of main bunds,
E_s = earthwork of side bunds, and
E_l = earthwork of lateral bunds.

The values of $E_s + E_l$ are taken 30% of E_m . Thus,

$$E_m = \text{cross-sectional area} \times \text{total bund length} = 100\,\frac{S}{VI} \times \text{cross-sectional area}$$

$$E_s + E_l = 0.3 \times 100\,\frac{S}{VI} \times \text{cross-sectional area} = 30\,\frac{S}{VI} \times \text{cross-sectional area}$$

$$E_t = E_m + E_s + E_l = 130 \times \frac{S}{VI} \times \text{cross-sectional area} \qquad (25)$$

Example 5.2. A bund of top width 40 cm bottom width 120 cm and height of 100 cm is to be constructed on 8% land slope with a horizontal interval of 20 m. The lateral and side bunds are also formed in the field. Calculate the total length and earthwork of the bund.

Solution

1. Length of main bund per hectare

$$L = \frac{10000}{HI} = \frac{10000}{20} = 500 \text{ m}$$

Length of side slope and lateral bunds = 30% of 500 = 150 m

Total length of the bund = 500 + 150 = 650 m

2. Computation of earthwork

(i) Earthwork of main bund per hectare

$$\text{Cross - sectional area} = \frac{0.4 + 1.2}{2} \times 1 = 0.8 \text{ m}^3$$

$$E_m = \text{cross-sectional area x length} = 0.8 \times 500 = 400 \text{ m}^3$$

(ii) Earthwork of side and lateral bunds:

$$= 0.8 \times 150 = 120 \text{ m}^3$$

$$E_t = E_m + (E_s + E_l) = 400 \text{ m}^3 + 120 \text{ m}^3 = 520 \text{ m}^3$$

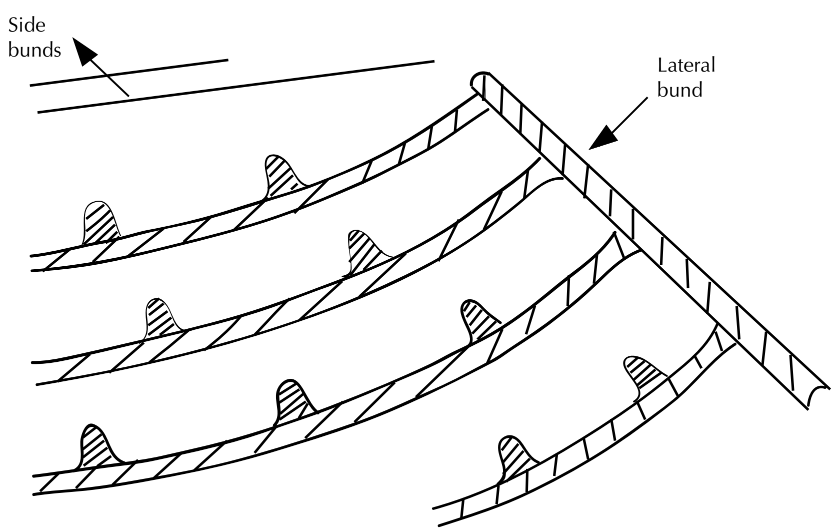


Figure 17. *Side bunds and laterals in bunding.*

Figure 18. *Contour bunding for crop production.*

5.5 Area lost due to bunding

It is calculated by multiplying the length of bund per hectare by its base width (b), i.e.

$$A_L = \frac{10000}{HI} \times b = \frac{100\,S}{VI} \times b \qquad (26)$$

This equation computes the area lost due to the main bund, but not the area lost due to side and lateral bunds. Usually, the area lost due to side and lateral bund is taken as 30% of the area lost due to main contour bund. Thus the total area lost due to bunding is:

$$A_{Lt} = \frac{100\,S}{VI} \text{ x b} + 30\% \;(\frac{100\,S}{VI} + \text{b}) = 1.3\; \frac{100\,S}{VI} \text{ x b} \qquad (27)$$

Example 5.3. Calculate the area lost per hectare for the conditions given in Example 3.

VI = HI x S/100 = 20 x 8/100 = 1.6 m

$$A_{Lt} = 1.3\; \frac{100\,S}{VI} \text{ x b} = 1.3 \text{ x } \frac{100 \text{ x } 8}{1.6} \text{ x } 1.2 = 780 \text{ m}^2$$

5.6 Field layout of bunds

Before constructing bunds, their centre line must be traced by pegs using line level strings of convenient length and graduated wooden staffs (rods). The staffs are graduated starting at 0 from the top and ending with 100 cm at the extreme bottom. The marking is made every 5 cm. Three persons, namely head string man, middle string man and rear string man make up the surveying party. The horizontal slope of the bund is determined based on the chosen distance between the two staffs. If the distance between the two staffs is chosen to be 10 m and a horizontal slope of the channel of the bund is decided to be 0.5%, then the rear string-man, who begins the operation from the waterway, ties his string on 0-mark of the rod and the head string-man ties on 5 cm mark (Figure 19). The middle string man tells the head string man to move up and down till the bubble of the line level is centred. Peg is then driven at the point where the rod was placed. The rear string-man then moves forward occupying the former position of the head string-man and the procedure of centring is carried out as explained above.

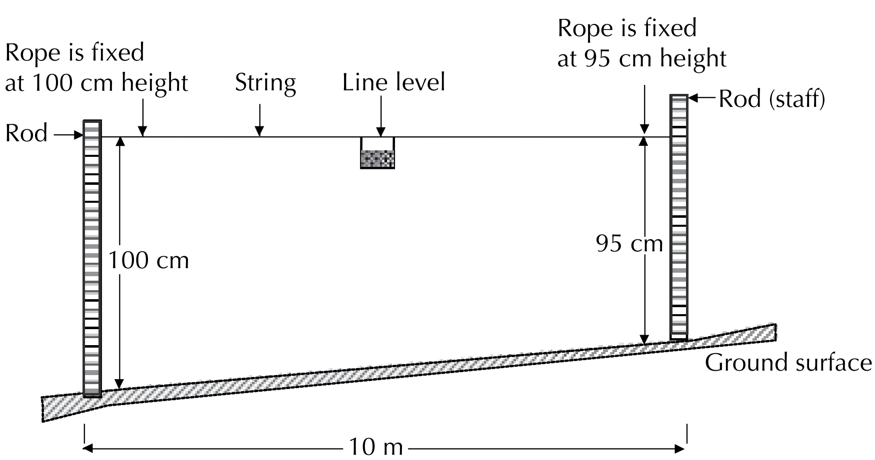


Figure 19. *Laying of the centre line of a contour bund at 0.5% horizontal slope.*

To lay down a vertical interval of one metre, the string shall be tied on the 100 cm mark of the up slope rod (staff), i.e. on the extreme bottom of the rod and the down-hill string shall be tied on 0-mark of the rod, i.e. on the extreme upper mark of the staff (Figure 20). At the middle of the string, joining the two rods, a line level is placed. The down slope string-man moves the rod up and down the slope till the middle string-man observes that the line level is centred. This point of the down slope rod will be marked as the starting point of the next contour bund having elevation difference of 1 m as compared to the previous contour bund.

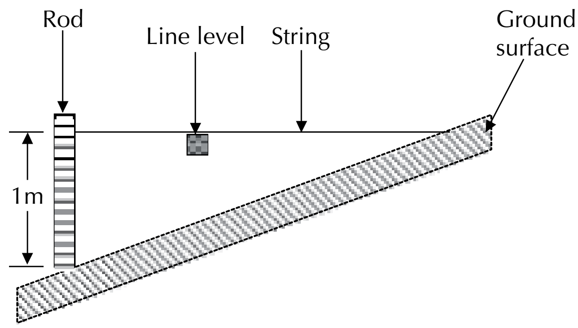


Figure 20. *Laying vertical interval of 1 m.*

5.7 Construction of bunds

The construction of a bund is always started from the top of the watershed area and from the waterway. If a bund is started from the bottom of a watershed area and if it is not completed in one season, then all water from the top of watershed area will destroy the lower one. Layout, digging, sloping, berm making, consolidation, making ramps and grassing are the main procedures to be followed in constructing bunds (Figure 21). From the centre line, 1 m on the upslope side and 1.5 m on the down slope side are marked. The 1 m width on the up slope side will be dug and the soil will be piled on the 1.5 m width down slope. The bund is dug approximately 30 cm deep (but this value can be less or more depending on the rainfall of the area) and sloped at 30^o on the up slope side (Figure 21). A berm is constructed on the down slope side of the channel to protect the lower edge. Ramps should also be made for carts, agricultural machinery, cattle or human path. Finally the bund has to be grassed. Contour bunds increase productivity by 25% in low rainfall areas. Continuous inspection and repair are required for contour bunds.

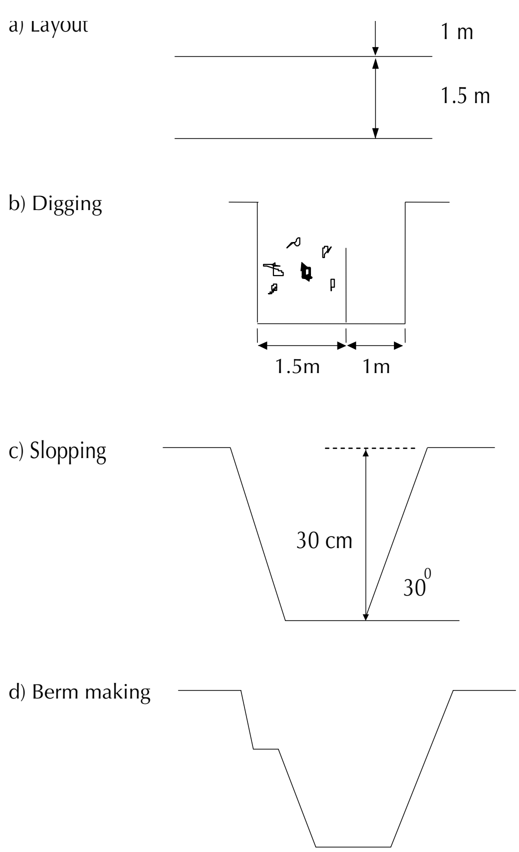


Figure 21. *Construction procedure of typical contour bund.*

Chapter 6 Terracing

A terrace is an earth embankment with a channel constructed across the slope at a fixed vertical interval and at an acceptable horizontal slope. Terraces are constructed to reduce erosion, to remove excess surface water, and to retain the maximum amount of moisture for crop production. Terracing is the most effective of several erosion control practices.

6.1 Types of terraces

Terraces are classified into three main classes as diversion, retention and bench type terraces. The primary aim of a **diversion terrace** is to intercept the overland flow and channel it across the slope to a suitable outlet. Diversion terraces are constructed on a small gradient usually 1:250 to the contour. The diversion terraces are again classified as magnum, Nichols, broad-based, and narrow-based type. The *magnum type diversion terrace* is constructed by taking the soil from both sides of the embankment. Taking the soil from the upslope side of the embankment only forms the *Nichols type diversion terrace*. The *broad based type diversion terraces* are constructed with embankment and channel occupying a width of 15 m. The *narrow based type* diversion terraces are only 3 to 4 m wide; the banks have steeper slopes, which cannot be cultivated. **The retention terraces** are level terraces, which are used for conserving surface water by storing it, as they are usually practised on hillsides. **Bench terraces** are platform like constructions along a slope, which is used to cultivate steep slopes. This type of terraces is generally constructed on slopes of 6 to 33°. Bench terraces are again classified as (1) level bench terraces, (2) bench terraces sloping outward, and (3) bench terraces sloping inward.

Level bench terraces consist of level top surface and are generally used in low rainfall areas with highly permeable soils (Figure 22a). Level bench terraces are sometimes called irrigated bench terraces, tabletop or paddy terraces. *Bench terraces sloping outward* are adopted in low rainfall areas with permeable soil (Figure 22b). For these terraces a shoulder bund is essential to provide stability to the outer edge of the terrace. Bench terraces sloping outward are also known as orchard type bench terraces. Bench terraces sloping inward are preferred in areas of heavy rainfall and less permeable soils, from where large portion of water is drained as surface runoff. Such a type of bench terrace has a provision to drain the runoff from its inner side by constructing a drainage channel (Figure 22c). The cross section of a typical inward sloping bench terrace provided with risers is shown in Figure 23.

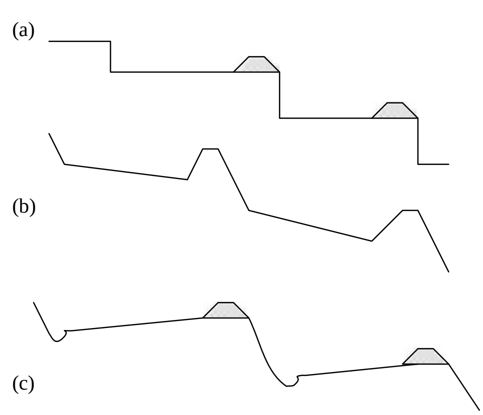
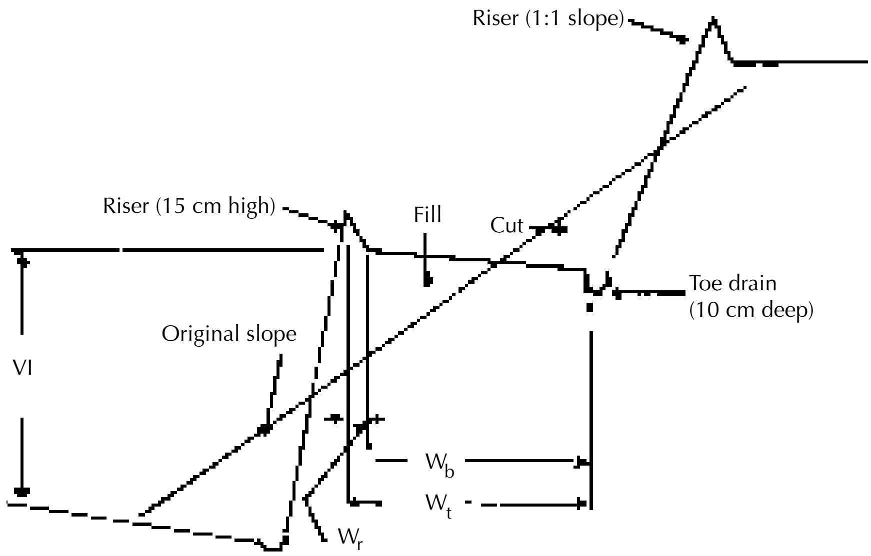


Figure 22. *Types of bench terraces.*



Note: W_b = width of the bench, W_t = width of the terrace, and W_r = width of the riser.

Figure 23. *Cross sectional view of inward sloping bench terrace.*

6.2 Terrace spacing

Terrace spacing is the vertical distance between the channels of successive terraces. For the top terrace the spacing is the vertical distance from the top of the hill to the bottom of the channel. This vertical distance is commonly known as vertical interval (VI). The computation of terrace spacing can be accomplished using the following steps.

1. Determine the maximum depth of the productive top soil
2. Find out maximum admissible depth of cut for the land slope of the field and crop to be grown based on the existence of maximum depth of productive soil range
3. After determining the depth of cut, find out the width of terrace using the equation

$$W = \frac{200\,D}{S} \tag{28}$$

Where S =average land slope, %

D = Depth of cut, m

W= width of terrace bench, m

4. Determine the vertical interval of terrace, using the following formulae:

(i) for batter slope 1:1

$$VI = \frac{SW}{100 - S} \tag{29}$$

(i) for batter slope 1.5:1

$$VI = \frac{2\,SW}{200 - S} \tag{30}$$

The following theoretical formula was also reported by Morgan (1986).

$$VI = L \sin \theta \tag{31}$$

where

$$L = \frac{V^{\frac{5}{2}} n^{\frac{3}{2}}}{(P - I)\ \cos\theta \sin^{\frac{3}{4}}\theta} \qquad (32)$$

in which, L is length of slope on hill side; V is maximum permissible flow velocity for a given soil; n is Manning's roughness coefficient, which is used as 0.2 for bare soil; P is rainfall intensity; I is infiltration capacity of the soil; and θ is slope angle. Many empirical formulas have been developed for calculating the vertical interval of terraces.

6.3 Terrace gradient

Gradients in the channel must be sufficient to provide good drainage and to remove runoff at non-erosive velocities. Level terraces have zero grades. In the uniform graded terrace the slope remains constant throughout its entire length. A grade of 0.4% is common in many regions; however grades may range from 0.1 to 0.6 percent, depending on soil and climatic factors. Recommended maximum velocities are 0.46 m/s for extremely erosive soils and 0.61 m/s for most other soils, when the roughness coefficient in the Manning's formula is taken as 0.03. Recommended minimum and maximum grades are given in Table 13.

Table 13. *Maximum and minimum terrace grades*

Terrace length (m)	Maximum slope (%)
30 or less	2.0
31 – 60	1.2
61 – 150	0.5
151 – 365	0.35
366 or more	0.3
	Minimum slope (%)
Soils with slow internal drainage	0.2
Soils with good internal drainage	0.0

The gradient of a terrace can also be determined based on the peak runoff rate produced from the upstream bench terraces using the following steps:

1. Compute the peak runoff rate from the upstream bench terraces. For the purpose rational formula can be used, which is given as:

   $$Q_{peak} = \frac{CIA}{360} \qquad (33)$$

   in which, Q_{peak} is peak runoff rate (m^3/s), C is runoff coefficient (dimensionless), I is intensity of rainfall for the duration equal to the time of concentration (mm/h) and A is watershed area of the upstream terrace (ha).

2. Calculate the drainage area of the terrace (A) using the following equation:

   $$A = \frac{LW}{10000} \qquad (34)$$

   in which, L is the length of the terrace (m) and W is the width of the terrace (m).

3. Select permissible flow velocity (V) for concerned soil of the area (Table 14).

Table 14. *Safe velocities*

SN	Soil conditions	Safe velocity m/s
1	Bare channel sand	0.5–0.6
2	Poor vegetation	1.0
3	Fair vegetation	1.25
4	Good vegetation	1.50

4. Find out the approximate value of cross-sectional area of the channel (Ac), using the relation:

$$Ac = \frac{Q_{peak}}{V} \qquad (35)$$

5. Calculate the mean hydraulic radius (R) of the obtained cross-sectional area (A) of the channel based on the wetted perimeter (P) of the channel.

$$R = A/P \qquad (36)$$

6. Compute the value of the terrace grade (S) using the Manning's formula as:

$$V = \frac{R^{\frac{2}{3}} S^{\frac{1}{2}}}{n} \qquad (37)$$

in which n is Manning's roughness coefficient.

6.4 Terrace width, length and cross-section

The widths of bench terraces vary with their need for which they are to be used after construction. Once the width of bench terrace is decided, the depth of cut or spacing of bench terraces may easily be calculated using the following formulae for different cases:

Case 1. When terrace cut is vertical

$$D = \frac{WS}{100} \qquad (38)$$

in which, D/2 is the depth of cut, W is width of bench terrace, and S is the percent land slope.

Case 2. When the terrace cut has 1:1 slope

$$D = \frac{WS}{100 - S} \qquad (39)$$

Case 3. When terrace cut has ½:1 slope

$$D = \frac{2WS}{200 + S} \qquad (40)$$

However, depending upon land slope and soil conditions, some adjustments are also made in between depth of cut and width of the bench terrace.

Terrace length is affected by size and shape of the field, outlet possibilities, rate of runoff (as affected by rainfall and soil infiltration), and channel capacity. The number of outlets should be a minimum consistent with good layout and design. Extremely long graded terraces are to be avoided. The maximum length for graded terraces generally ranges from about 300 to 500 metres, depending on local conditions. The maximum applies only to that portion of terrace that drains toward one of the outlets. There is no maximum length for level terrace.

A **terrace cross-section** should provide adequate capacity, have broad farmable side slopes, and be economical to construct with available equipment.

6.5 Construction of bench terraces

A variety of equipment is available for terrace construction. Terracing machines include the bulldozer, pan or rotary scraper, motor patrol and elevating grader. Smaller equipment, such as mould board and disk ploughs are suitable for slopes less than about 8%, but the rate of construction is much less than with heavier machines. The following rules are to be followed in constructing terraces:

1. Build the outlet 2 years before constructing terraces.
2. Start building from the outlet and top of the watershed.
3. Build terraces when the soil is neither too wet nor too dry.
4. Compact the soil for every 15 cm of fill.
5. Give allowance of 10% for settlement of fill.
6. Check horizontal and reverse grade in case of bench terrace.
   Reverse slope is the slope of the bench towards the up slope.
   Horizontal slope is the slope of a terrace along its length.
7. Make the riser slope 1:1.

A cross-section of a typical bench terrace is shown in Figure 23.

The earthwork involved during construction of different types of bench terraces can be computed using the following relationships:

(a) For level bench terraces

$$E_W = 1250VI = 1250 \frac{WS}{100} = 12.5WS \qquad (41)$$

(b) For inward sloping bench terraces

$$E_W = 1250VI = 1250 \frac{WS + s}{100} = 12.5W(S + s) \qquad (42)$$

(c) For outward sloping bench terraces

$$E_W = 1250VI = 1250 \frac{WS - s}{100} = 12.5W(S - s) \qquad (43)$$

where,

E_w = earthwork per hectare (m^3),
W = width of terrace (m),
S = land slope (%),
s = inward or outward slope of the bench (%).

The cost of earth moving is calculated by multiplying the rate of earthwork to the total volume of the earthwork made during terrace construction. The cost of bench terracing is governed by the earthwork, its rate and method employed for earth work (i.e. manual or machineries).

6.6 Areas lost in bench terracing

Bench terracing involves the loss of cultivable area due to terrace slope and its construction. It can be calculated using the following relationships:

Case 1. When better slope is 1:1, the area lost may be equal to:

$$A_L = \frac{S + 200}{\frac{200}{S} + \frac{S}{100}} \tag{44}$$

in which, A_L is the percentage area lost and S is the land slope in percent.

Case 2. When better slope is ½:1

$$A_L = \frac{S + 100}{\frac{200}{S} + \frac{S}{100}} \tag{45}$$

Example 6.1. On a hilly land of 15% slope a bench terrace of 2.5 m vertical interval with a better slope of 1:1 is proposed to be constructed. Calculate the following parameters of the bench terrace: (a) width, (b) length per hectare, (c) earthwork, and (4) area lost

Solution: For better slope of 1:1

(a) Using Equation (39): $W = \frac{D(100 - S)}{S} = \frac{2.5(100 - 15)}{15} = 14$ m

(b) $L = \frac{10000}{W + VI} = \frac{10000}{14 + 2.5} = 606.06$ m

(c) Using Equation (41): E_w per ha = 12.5WS = 12.5 x 14 x 15 = 2625 m^3

(d) Using Equation (44): $A_L = \frac{S + 200}{\frac{200}{S} + \frac{S}{100}} = \frac{15 + 200}{\frac{200}{15} + \frac{15}{100}} = 15.9\%$

After construction of the bench terrace, the next step involves its maintenance. Normally, the following points are considered for the maintenance of bench terraces.

1. Shoulder bund should be planted with permanent grasses
2. Toe part of the bund should be avoided from ploughing operation
3. Batter slopes should be protected by establishing deep-rooted grasses

Terraces should be inspected and repaired on time. Failure of one terrace can destroy all of the terraces below it.

Figure 24. *Typical example of terraces on steep slope.*

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Module 2

Water harvesting and development for improving productivity

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Introduction

It is well known that the pressure on land is increasing every day due to population growth, causing more and more use of marginal lands for agriculture. Agriculture is only possible when there is availability of water. By water harvesting during rainy seasons, water availability can be formed. The phrase water harvesting was first used in Australia by HJ Geddes (Suresh 2002) to denote the collection and storage of any farm water either runoff or creek flow for irrigation use. Currently, the terminology 'water harvesting' is used to indicate the collection of any kind of water for domestic, agricultural, or other purposes. Water is harvested and directed either directly onto cropped fields, or into various types of natural or man-made storage structures. A large variety of storage technologies are used in Eastern and Southern Africa and many of these are described and illustrated in Mati (2006), Ngigi (2003) and IWMI (2006). For water harvesting structures to be successful, the village communities must participate in the planning and construction of the structures and accept responsibility for their operation and management.

A major reason for the low and erratic rate of growth in agricultural production is the highly uncertain and unpredictable rainfall, combined with low soil fertility (FAO 2003). Even in years of 'average' rainfall, a shortfall during critical periods of crop growth often leads to widespread crop failure. Therefore, water storage is absolutely crucial for stabilizing and increasing crop yields (FAO 2003). Water can be stored in many ways: large and small dams, aquifers, on-farm storage tanks, and in the root zone of crops.

The sources of water that can be harvested are the roof water, surface flow and even perennial streams (Table 1). The harvested water can then be used for agriculture, domestic water supply, fisheries etc. The design principle of water harvesting structures is similar to the other hydraulic structures requiring a wide range of input.

Table 1. *Types, techniques and storage of water harvesting*

	Roof harvesting			Floodwater harvesting		Groundwater harvesting	
	Roof and courtyard WH	Micro-catch-ment WH	Macro-catchment WH	FWH within stream bed	Floodwater diversion	Sand storage dams	Horizontal wells
Techniques used	Sealed, paved, compacted, or smoothened surfaces	Contour bunds, pitting, bench terraces,	Stone dams, reservoirs, etc.	Percolation dams etc.	Wild flood-ing, water dispersion, water dis-tribution	Sub-surface dams	Artesian wells
Kind of storage	Cisterns, ponds, jars, tanks	Soil pro-file	Soil profile, cistern, ponds, reservoirs	Reservoirs	Ponds	Substrate profile	Soil profile ponds
GW recharge	No	no	medium	medium	medium	large	large

This module looks at the various techniques used in water harvesting, the planning, construction and management of such provisions.

Chapter 1 Rainwater harvesting

There is a growing interest in the large range of low-cost agricultural water management technologies in semi-arid developing countries. This is in response to the observation that unreliable water supply is one of the biggest threats to the food security of poor small farmers. The vast majority of the rural poor rely on rain-fed land for their survival, making them vulnerable to the highly variable and unpredictable rainfall. Periodic drought and famine are the result, especially in many sub-Saharan African countries (IWMI 2006).

Rainwater harvesting is also widely used for the provision of drinking water, particularly in the rural areas of Europe, Asia, and Africa. Even if the importance of rainwater diminishes where there is piped water supply, rainwater continues to be the only source of domestic water supply on some tropical islands. People live in scattered or nomadic settlement in arid and semi-arid regions and it is hard to supply them with piped water. Therefore, rainwater harvesting is very necessary in such regions. Rainwater harvesting techniques can be classified as: (1) roof harvesting; (2) runoff harvesting; and (3) flood harvesting.

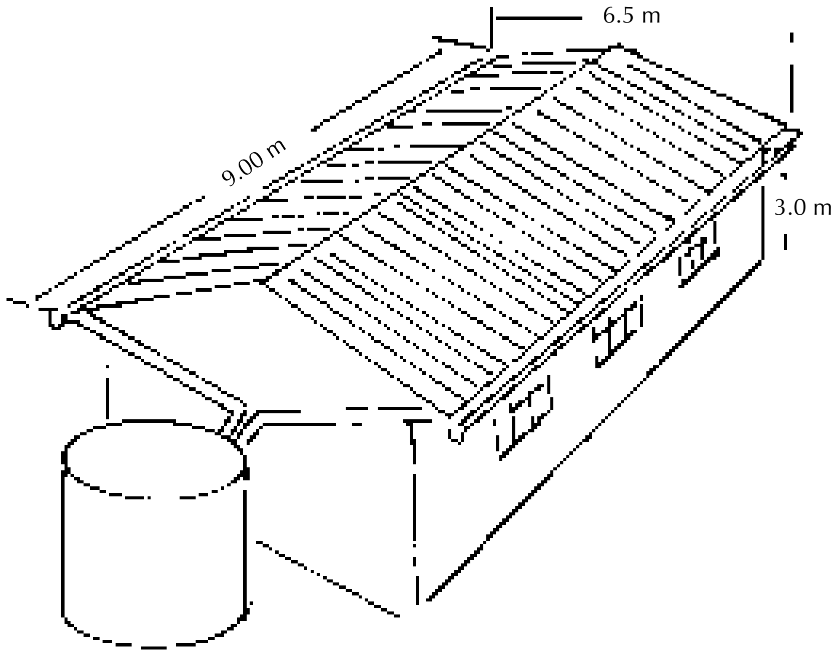
1.1 Roof harvesting

The roofs of houses can provide reasonably pure water (Figure 1). However, thatched or lead roofs are not suitable for roof harvesting because of health hazards. A gutter can collect the water and then lead to a down pipe. The roof guttering should slope evenly towards the down pipe, because, if it sags, pools that can provide breeding places for mosquitoes will be formed.

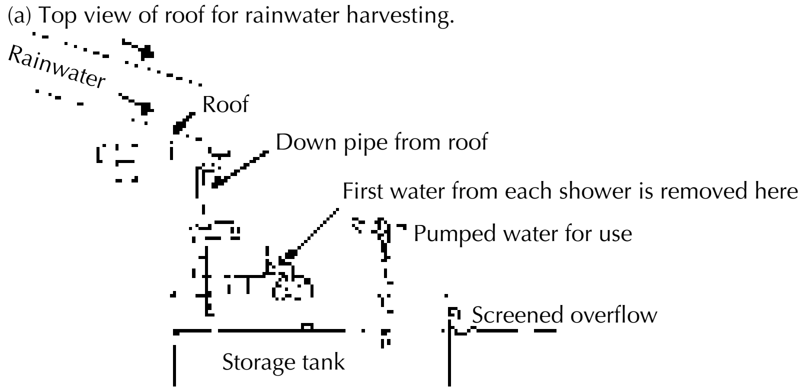
During dry periods, dust, dead leaves and bird droppings will often accumulate on the roof; however the first new rains should wash these off. The first water from each shower should be diverted from the clear water container and allowed to run to waste. To further safeguard the quality of the collected rainwater, the roof and guttering should be cleaned regularly. A wire mesh should be placed over the top of the down pipe to prevent it from becoming clogged with washed-off material.

A simple sanitary method of collecting rainwater is illustrated in Figure 2. The gutter collects water from the roof and drains into an angled pipe. One piece of the angled pipe leads vertically downward to a small waste drain tank (20 to 25 litres), while the other piece is connected horizontally to a collection tank or reservoir. When rain falls, the first 10 to 15 minutes of rainwater washes off dirt, which might be on the collecting surface and flows into the waste drain tank. After this tank is full, the rest of the rainwater (by this time clean water) flows into the collection tank. The wastewater in the drain tank should be emptied before the next rainfall. Figure 3 shows some different methods of roof water harvesting.

The size of a roof depends on the size of the house. The effective area of the roof and local annual rainfall will largely determine the volume of the rainwater that can be collected through roof catchment. In a region having an average annual rainfall of 800 mm, the amount of rainfall which can be collected by a roof measuring 7 m × 9 m (in plan) in a year can be estimated as: 7 m × 9 m × 0.8 m = 44.8 m^3/year = 44,800 litres/year or about 120 litres/day on average. This amount may fulfil the basic drinking and domestic water requirement of a family of 10 persons in a water scarcity area.



(a) Top view of roof for rainwater harvesting.



(b) Sketch of down pipe and storage tank for roof harvesting.

Figure 1. *Water harvesting from roof catchment.*

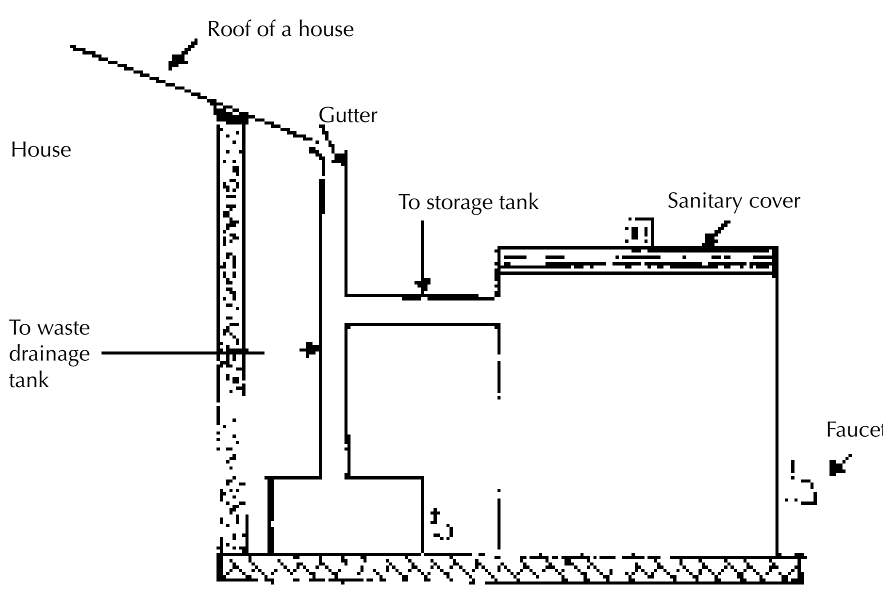


Figure 2. *Sketch of a simple sanitary installation for collecting rainwater.*

(a) Rainwater harvesting from roofs provides clean drinking water for domestic use and small livestock.

(b) Furrow alongside the house to divert water falling from the roof into underground tank.

(c) Improved lining of the furrow, which catches water from the roof—without gutters.

Courtesy: IWMI (2006).
Figure 3. *Different methods of collecting water from roof.*

1.2 Runoff harvesting

Runoff harvesting can be done over the short or long term. The short-term purpose for runoff harvesting can be for small-scale water use. The long-term runoff harvesting is mainly done for building a big water stock for the purpose of irrigation, livestock or fisheries. Either constructing reservoirs or big-sized ponds are methods of long-term runoff harvesting.

1.2.1 Short-term runoff harvesting techniques

Rainwater can be collected from the ground surface (Figure 4). As it rains, part of the water will wet the ground and be stored in depressions, or lost through evaporation or infiltration. A considerable reduction of such water losses can be given by laying tiles, concrete, asphalt or plastic sheeting to form a smooth impervious surface on the ground surface. Another method involves the chemical treatment of the soil. Also occasionally, simply compacting of the surface of the ground is adequate.

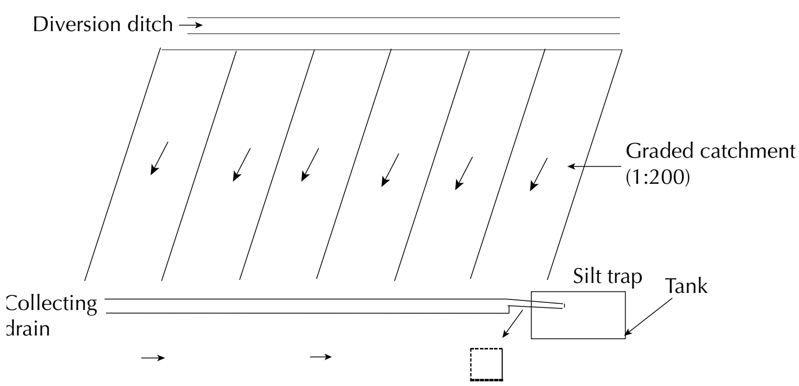


Figure 4. *Ground surface catchment.*

The slope and water tightness of the top layer of an area affects the amount of rainwater that can be collected. In rolling hills careful soil compaction may be sufficient to attain good harvesting efficiency. In areas with flat land the ground surface may need to be covered with tiles, corrugated iron sheets, asphalt, cement, or even materials such as heavy butyl rubber or thick plastic sheets. These materials may catch as high as 90% of the rainfall runoff of the catchment area. Such cover has an advantage that it needs low maintenance and has a long useful life. However, these materials are generally too expensive for use over large ground surface. The following surface coating methods may be relatively cost saving:

I. Asphalt the area in two coats. Then reinforce with plastic or fibreglass and cover with gravel.
II. Spread paraffin wax on the surface as granules, which melt in the sun.

Treating the top layer of the soil with chemicals such as sodium salts, bitumen or tar can also have good results. Sodium salts may be applied, thus converting clay particles to form an impervious layer. A bitumen or tar coating may be sprayed over the ground to block the soil pores. Such treatment need not be expensive and can be repeated at regular intervals (Once every few years) in order to maintain the water tightness of the ground surface. Treated ground surface of sufficient size can provide a domestic water supply for a number of families, or even a whole village community, but they need proper management, maintenance, and protection against damage and contamination. It may be necessary to provide fencing or hedging. An intercepting drainage ditch at the upper edge of the watershed and a raised curb around the watershed would be needed to avoid the inflow of polluted surface runoff. Trees and shrubs surrounding the watershed can be planted to limit the entry of wind blown materials and dust into the watershed.

The collected water can be stored above or below the ground. The storage should be provided with adequate enclosure to prevent any contamination from humans or animals, leaves, dust, or other pollutants entering the storage container. A tight cover should ensure dark storage condition so as to prevent algal growth or breeding of mosquito larvae. Open containers or storage ponds are generally unsuitable as source of drinking water. Below ground storage facilities keep the water cool, prevent evaporation, and save space.

There are several types of storage facilities. The storage can be directly moulded into the ground by simply compacting the earth (Figure 5). Cement applied by hand may be used for plastering the walls of the excavation, or simple plastic sheeting can be used. Sand filters and plastic sheets can also give good results (Figure 6). Wooden rainwater barrel, thin-walled cement containers, clay pots or barrels, corrugated iron tanks etc can be used for collecting rainwater. Figure 7 shows methods of storing water in closed pits.

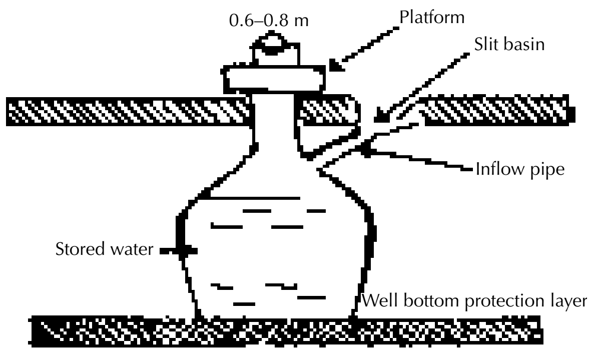


Figure 5. *Underground rainwater storage well.*

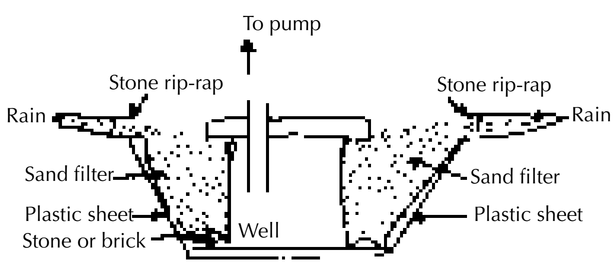
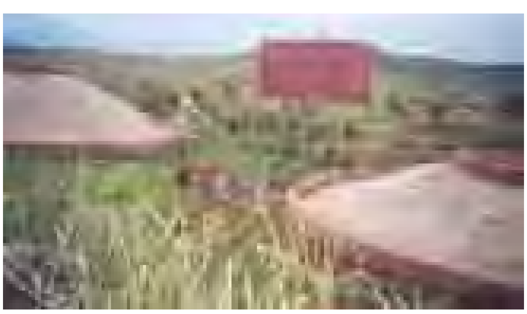


Figure 6. *Plastic sheet and sand filter used in underground storage of rainwater.*



(a) Water storage in closed pits/underground tank lifted with small-scale water lifting technology, for micro irrigation technology application

(b) Closed pit prepared for catching rain water
Figure 7. *Water storage in closed pits.*

1.2.2 Long-term runoff harvesting techniques

The most common long-term runoff harvesting structures are dugout ponds and embankment type reservoirs. Dugout ponds are constructed by excavating the soil from the ground surface. Groundwater, or surface runoff or both may feed into these ponds. Construction of these ponds is limited to those areas, which have land slope of less than 4% and where water table lies within 1.5 to 2.0 meters depth from the ground surface. Dugout ponds involve more construction costs and therefore are generally recommended when embankment type ponds are not economically feasible for construction.

The embankment dam is constructed by damming across a valley or depression of a watershed. The storage capacity of the reservoir is determined on the basis of water requirement for various demands and available surface runoff from the watershed. Embankment type reservoirs are again classified according to the purpose for which they are meant, namely: irrigation dams, silt detention dams, farm ponds, water harvesting ponds, and percolation dams.

1.3 Floodwater harvesting

To harvest floodwater, wide valleys are reshaped and formed into a series of broad level terraces and floodwater is allowed to run through them. The floodwater is spread on these terraces, where some of it is absorbed by the soil, which is used later on by the crops grown in the area. Some techniques, which are used in floodwater harvesting, are (a) graded bunds (b) check dams (c) sand dams and (d) flood control reservoirs. Runoff water is diverted to the area covered by graded bunds by constructing the diversion ditches, where crops are irrigated by flooding. Spillway can be provided for the overflow.

Small rock or concrete check dams are constructed across depressions to control the flow and allow infiltration into the subsurface under the bed to replenish the aquifer. The water, which is stored in the aquifer, can be abstracted through wells or boreholes and then used. This system includes various benefits such as less loss of water due to evaporation than the surface water reservoirs, fewer problems of siltation and cheaper construction.

Water harvesting by the use of sand dams consists of constructing a dam across a valley or depression. The silt load of the runoff will deposit over the bed. This can sometimes lead to the bottom of the valley being raised due to deposition of sand particles. In this characteristic, the silted part of the area is known as a silt reservoir. Water flowing through the valley is filled into pore spaces of the sand reservoir, thus creating a water body. This method has the advantage of losing less water through evaporation. The reservoirs constructed at suitable sites for controlling floods are known as flood control reservoirs. They should be well equipped with self-operating outlets for letting out the harvested water into the stream or canal below the reservoir.

Chapter 2 Construction of rainwater harvesting tank

2.1 Selection of site for the tank construction

- Observe the direction of the surface flow of rainwater in the land.
- The tank may be subjected to cracks due to the root zone activities (i.e. ramification), therefore, it is advisable not to construct the tank in close proximity to large trees.
- The tank should be close to the area of cultivation to ensure ease of irrigation.
- The tank should not be in close proximity to the house or to paths/roadways as it is possible for children and even negligent adults to fall in. As an additional security measure, construct a fence around the tank.
- The opening of the tank should be to the direction of the flow of rainfall. It is not advisable to obstruct patterns of natural flow of water as there is a possibility of mud and other waste getting into the tank. (Mud filters function only when the water flows directly through them).

Further issues to consider

- If a very strong current of water is flowing it could place the tank in jeopardy.
- If by construction of the tank, the natural water flow is obstructed, soil erosion can occur and crops can consequently be destroyed.

2.2 Tank construction procedures

- Clear the selected land thoroughly. Flattening the land is important for ease of taking measurements.
- It is advisable to construct a circular tank as it will withstand greater pressures.
- Determine the quantity of water required for irrigation purposes.

Additionally the following factors should be considered:

- The rainfall pattern of the area. (If the area experiences regular rainfall throughout the year, a small tank of 4000–5000 litres would suffice, whereas in particularly dry areas which experience dry spells for about 6 months of the year, it would be beneficial to store as much water as possible.)
- The extent of land, which is proposed to be cultivated.
- The amount of investment that can be made.

The tank should not be more than 1.75 m in depth in order to withstand the pressure of the water. The less deep the tank is constructed makes cleaning and use of the tank easier. Table 2 can be used as a guide to determine the radius of the tank.

Table 2. *Capacity according to the radius of the tank*

Capacity of tank (litres)	Radius of tank (meters)
5000	0.9
6000	1
7000	1.125
8000	1.2
9000	1.275
10,000	1.35
11,000	1.425

- Take a length of rope as long as the radius and tie it to a wedge. Plant the wedge at the place you want to be the centre of the tank and draw a circle (Figure 8).

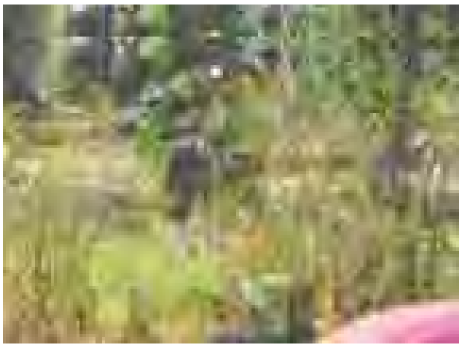


Figure 8. *Measurement taken for radius of the tank.*

- Now dig-out the soil within this circle (Figure 9).

Figure 9. *Pit for the tank construction.*

- The tank should have a slope of about one foot from the periphery to the middle of the tank.
- After the soil has been removed, a 10 cm slab of concrete has to be laid at the bottom of the tank. The ratio of sand, cement and gravel in the concrete mixture should be 1: 2: 4
- After the slab of concrete is hardened and has completely dried, construct the walls one foot in height from the inlet with a width of one brick (Figure 10). It is important to use bricks with dimensions of: 5 cm × 10 cm × 23 cm for this purpose. The cement mixture should have a ratio of cement to sand of 4:1.4

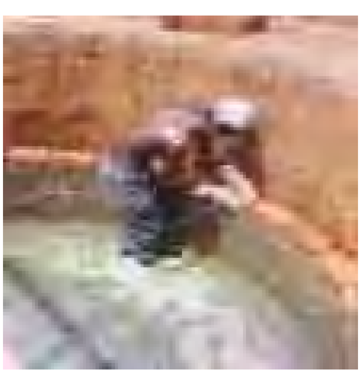


Figure 10. *Wall construction of the tank on the concrete base.*

- As the water inlet is connected to the tank at the ground level, hence, the water inlet wall should not be raised above the surface level (Figure 11).

Figure 11. *Measurement taken for the inlet construction.*

- The mud filters are attached to the water inlet and therefore the door has to be sturdy. As depicted in the picture below, a concrete slab measuring in metres 0.75 m × 1 m (height and length) should be laid near the door.
- When constructing the water inlet (Figure 12), it is necessary to face it in the direction of the natural water-flow of the garden. As the mud filters should be placed around this door, a drain should be constructed close to the inlet of 0.5 meters (near the door) and 1 metre width. The total length of this drain should be 1 metre.

Figure 12. *Concrete base for the inlet construction.*

Mud filters

- Various waste items are present in flowing water. Mud, sand and gravel deposits in the tank will lessen the quantity of water that can be stored in the tank. Therefore mud-filters are used as a simple method of reducing the flow of waste items into the tank.
- Construct 2 brick bunds in the shape of a 'V' on either side of the drain, which is constructed near the inlet. Two other small bunds of about one brick (10 cm) high should be constructed across the 'V' shaped bunds. They should be placed in 45 cm and 85 cm from the inlet.
- From these 2 small bunds, the one closer to the tank should be a 0.75 cm lower than the inlet bund (Figures 13 and 14). The external bund should be constructed 0.75 cm lower than the internal bund. By construction of bunds with a gradual rise towards the tank, it is possible to retain waste items that flow in with the rainwater, in silting chambers located within the bunds.

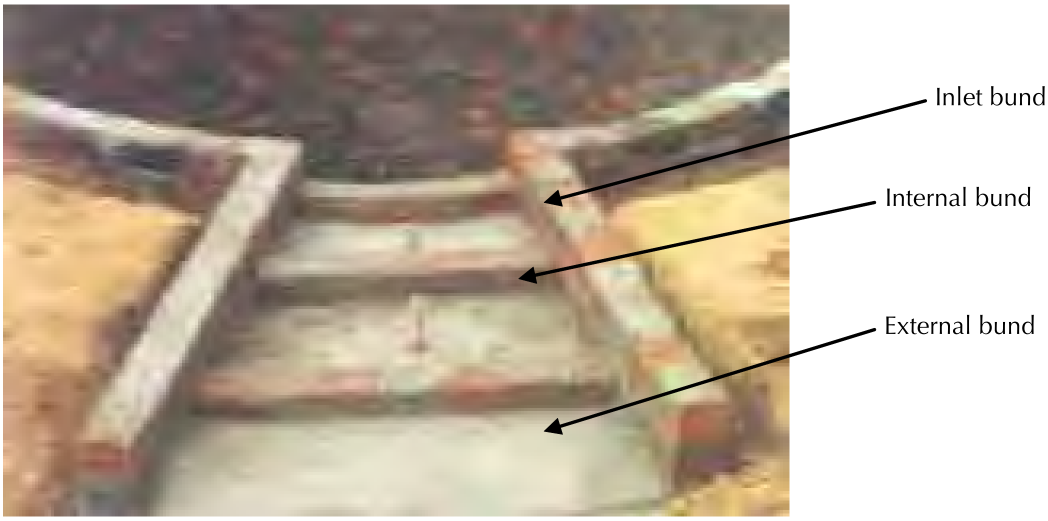


Figure 13. *Bunds of the inlet before plastering.*

Figure 14. *Inlet of the runoff tank after plastering.*

- In the opposite direction of the inlet-door, a 22 cm spill space (outlet) should be constructed in order to facilitate the flow of excess water (Figures 15 and 16). It is important to make this a 1.25 cm higher than the inlet-door.

Figure 15. *Outlet of the tank.*

Figure 16. *Completed tank before plastering.*

- Now plaster the tank completely with cement. In this case you should plaster the outside of the tank about 15 cm above the ground level (Figure 17).

Figure 17. *Plastering the tank.*

- An empty space of several centimetres will be observed, which has been left around the tank during the construction, to facilitate the process of construction. This empty space should be filled tightly with sand. Sand is used for the filling of this space as it can be packed tightly and is not easily subjected to decomposition. In the instance of repairs being needed for the tank, this sand layer will allow access to the tank.
- If maintained properly, it will be possible to use the rainwater-harvesting tank with ease, for about 15 years.

2.3 Best practices of operation and maintenance

- When the water in the tank becomes empty, remove all soil deposits and other waste products from the bottom of the tank and clean it well (Figure 18).

Figure 18. *Run off rain water collection to the tank.*

- A small thatched hut and fence can be constructed around the tank to reduce the evaporation of water and for the security of children and domestic pets (Figure 19).
- Do not let water-plants grow in the tank as these will increase water loss through evapotranspiration.
- Still waters are breeding grounds for mosquitoes, therefore fish which prey on mosquito larvae (e.g. 'Korali'—*Oreochromis mossambicus* can be introduced into the tank).

Figure 19. *Thatched hut, fence protecting the rainwater harvesting tank.*

A completed rainwater harvesting tank after completion and being filled with water looks as in Figure 20.

Figure 20. *A completed rainwater-harvesting tank.*

Chapter 3 Water harvesting techniques

Water harvesting techniques can be grouped into four groups, namely, microcatchments, macrocatchments, floodwater harvesting and storage. A microcatchment includes natural depressions, contour bunds (ridges), inter-row water harvesting, terraces, semi-circular and triangular bunds, eyebrow terraces, valerian-type microcatchments, pits, Meskat and Negarim. The macrocatchment consists of techniques such as stone bunds, large semi-circular bunds, trapezoidal bunds, and hillside conduit systems.

3.1 Micro-catchments

3.1.1 Contour bunds (ridges)

Contour bunds (ridges) for trees

The bunds follow the contour of the land at close spacing and, by the provision of small earth, the system is divided into individual microcatchments. Contour bunds for planting trees are shown below (Figure 21). Whether mechanized or not, this system is more economical than Negarim micro-catchments, 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 micro-catchments water harvesting techniques, the yield of runoff is high, and when designed correctly, there is no loss of runoff out of the system.

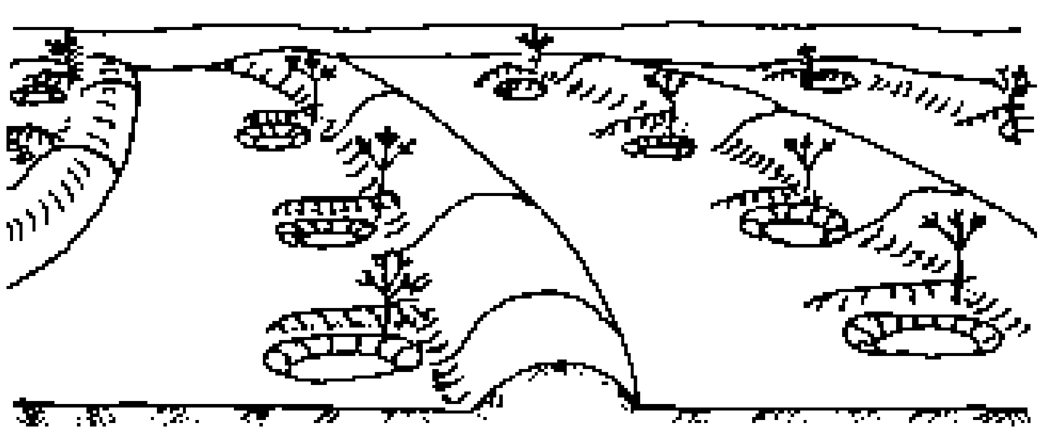


Figure 21. *Contour bunds for trees.*

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 (Figure 22). Infiltration pits are excavated in the junction between ties and bunds. A diversion ditch protects the system where necessary.

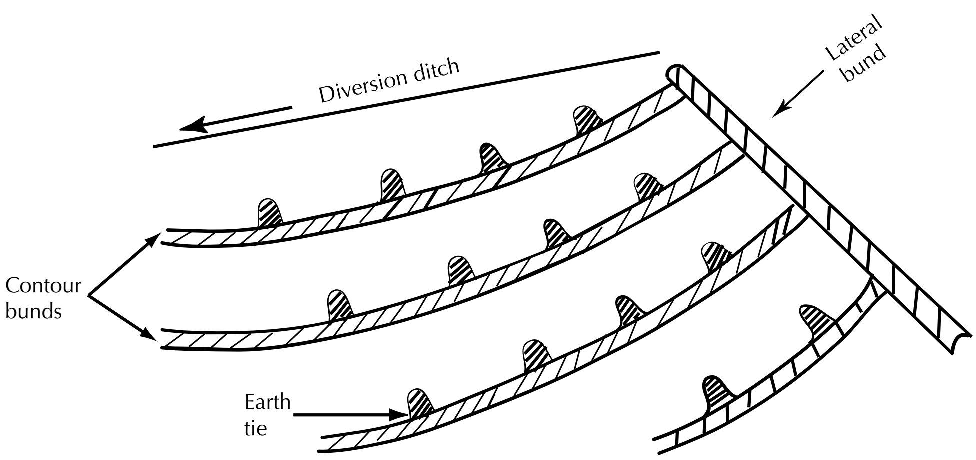


Figure 22. *Contour bunds for trees: Field layout.*

iv. Unit microcatchment size

The size of microcatchment is around 10–50 m^2 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 machines often make bunds 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 23).

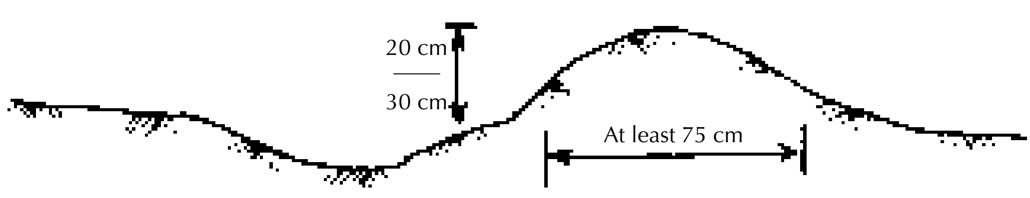


Figure 23. *Bund dimensions.*

Bunds should be spaced at either 5 m or 10 m apart (Figure 24). Cross-ties should be at least 2 metres long at a spacing of 2 m to 10 m. 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^2. This corresponds to 10 m bund spacing with ties at 2.5 m spacing or 5 m 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 (Figure 25). A pit size of 80 cm × 80 cm and 40 cm deep is usually sufficient.

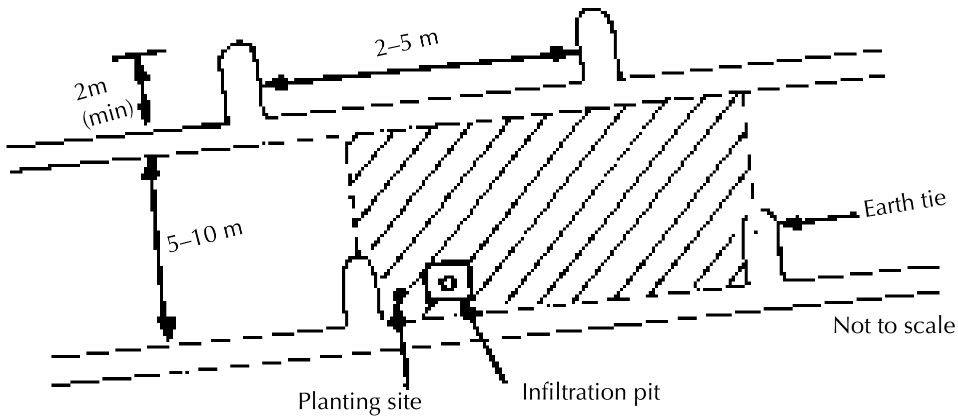


Figure 24. *Microcatchment unit.*

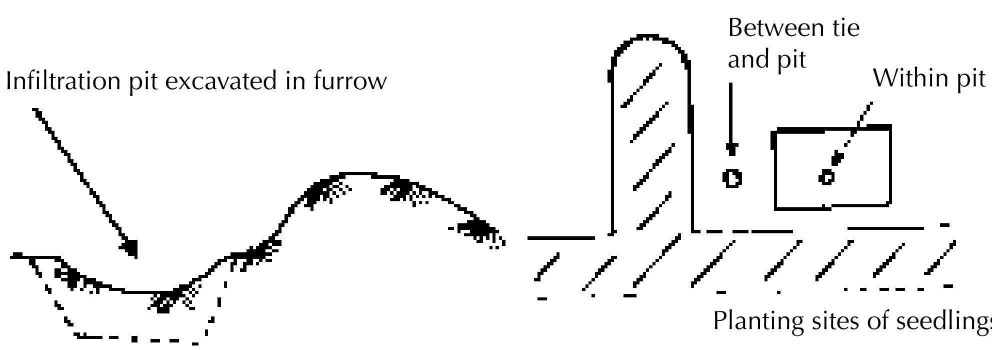


Figure 25. *Infiltration pit and planting sites.*

Contour ridges for crops

Contour ridges, sometimes called contour furrows or micro-watersheds, are used for crop production. Ridges follow the contour at a spacing of between 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 (what is tilling? Not introduced before). Using contour ridges for crops are not yet a widespread technique.

Figure 26. *Contour ridge system.*

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 down slope 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 27).

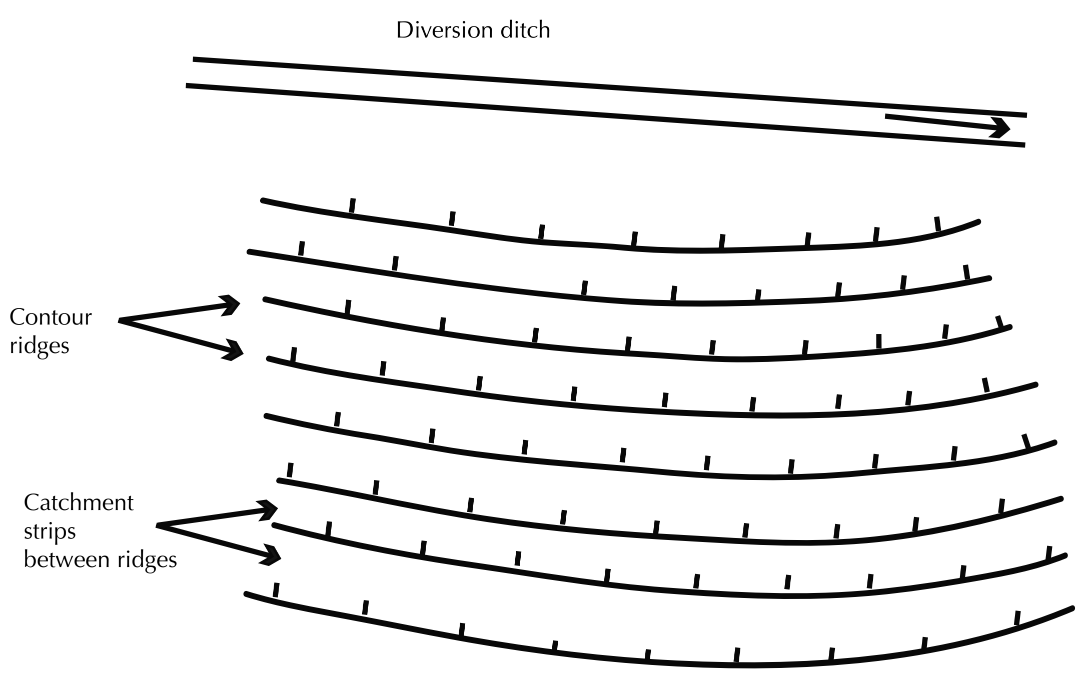


Figure 27. *Contour ridges: Field layout.*

iv. 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 should be sufficient. If bunds are spaced at more than 2 metres, the ridge height must be increased (Figure 28).

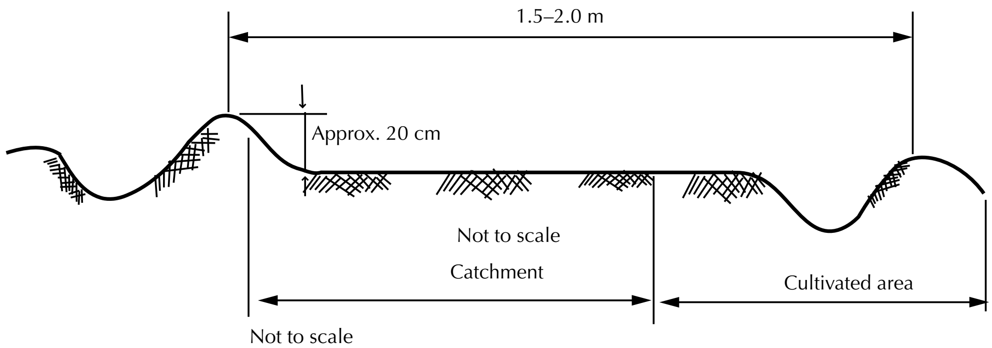


Figure 28. *Contour ridge dimensions.*

3.1.2 Semi-circular bunds

Semi-circular bunds are earth embankments in the shape of a semi-circle with the tips of the bunds on the contour (Figure 29). 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.

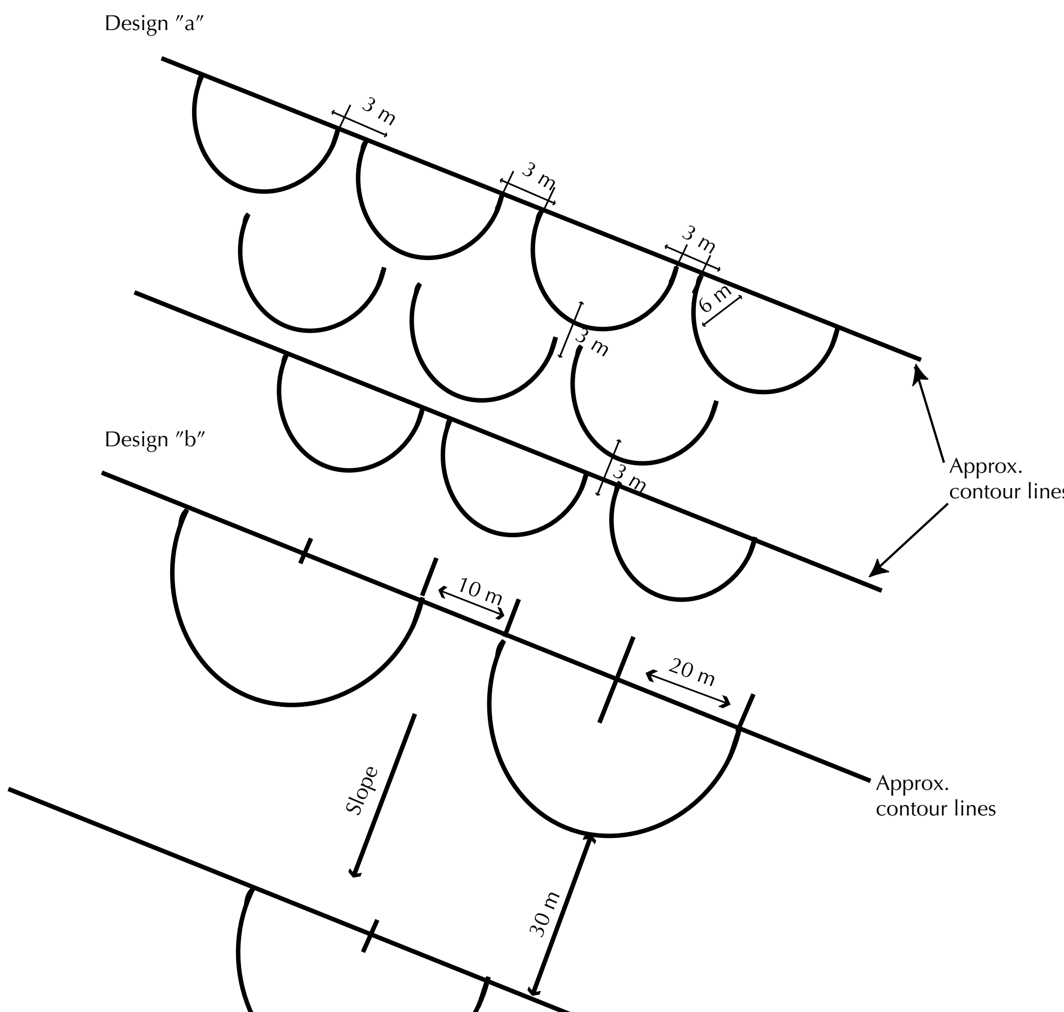


Figure 29. *Semi-circular bunds: Field layout.*

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%.

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 (Figure 30). 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, or 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 that are set on the contour.

iii. Bund design

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.

Layout and construction of semi-circular bunds

Step One

- Stake out contour by line level or water tube level

Step Two

- Use a tape measure to mark the tips of the bunds on the contour
- Mark the centre point between the tips with a peg
- Fix a piece of string of the length of the radius at the centre peg
- Swing the end of the strip from one tip to the other

- Mark the line of the swing with pegs or small stones

Step Three

- Stake out and construct the bunds in the second and all other
- Rows are in the same way but in staggered rows

Step Four

- Excavate a small trench inside the bund
- If applicable, put the fertile topsoil aside and use subsoil to build the bunds
- Construct the bunds in layers of 10–15 cm; compact each layer and wet it if possible

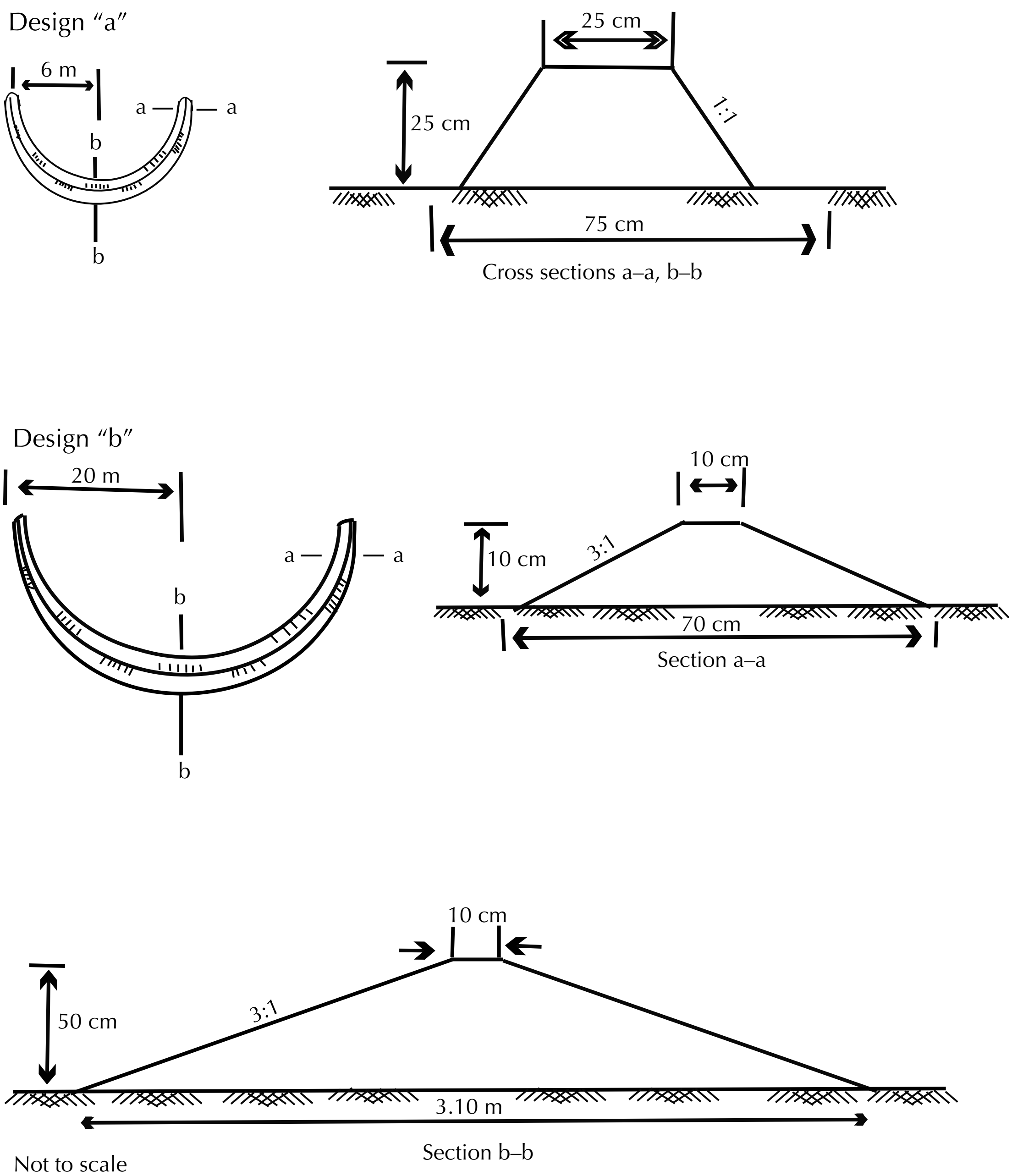


Figure 30. *Semi-circular bund dimensions.*

A semi-circular bund with acacia tree is shown in Figure 31.

Figure 31. *Semi-circular bund with acacia tree.*

Layout and construction of semi-circular bunds

Step One

- Stake out contour by line level or water tube level

Step Two

- Use a tape measure to mark the tips of the bunds on the contour
- Mark the centre point between the tips with a peg
- Fix a piece of string of the length of the radius at the centre peg
- Swing the end of the strip from one tip to the other
- Mark the line of the swing with pegs or small stones

Step Three

- Stake out and construct the bunds in the second and all other rows in the same way but in staggered rows

Step Four

- Excavate a small trench inside the bund
- If applicable, put the fertile topsoil aside and use subsoil to build the bunds
- Construct the bunds in layers of 10–15 cm; compact each layer and wet it if possible

A semi-circular bund filled with water is shown in Figure 32.

Figure 32. *Semi-circular bunds.*

3.1.3 Negarim

Negarim micro-catchments 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. Negarim 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 (Figure33). Besides harvesting water for the trees, it simultaneously conserves soil. Negarim microcatchments are relatively easy to construct.

Figure. 33. *Negarims with bushes. Photo: Oweis.*

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, and 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 34).

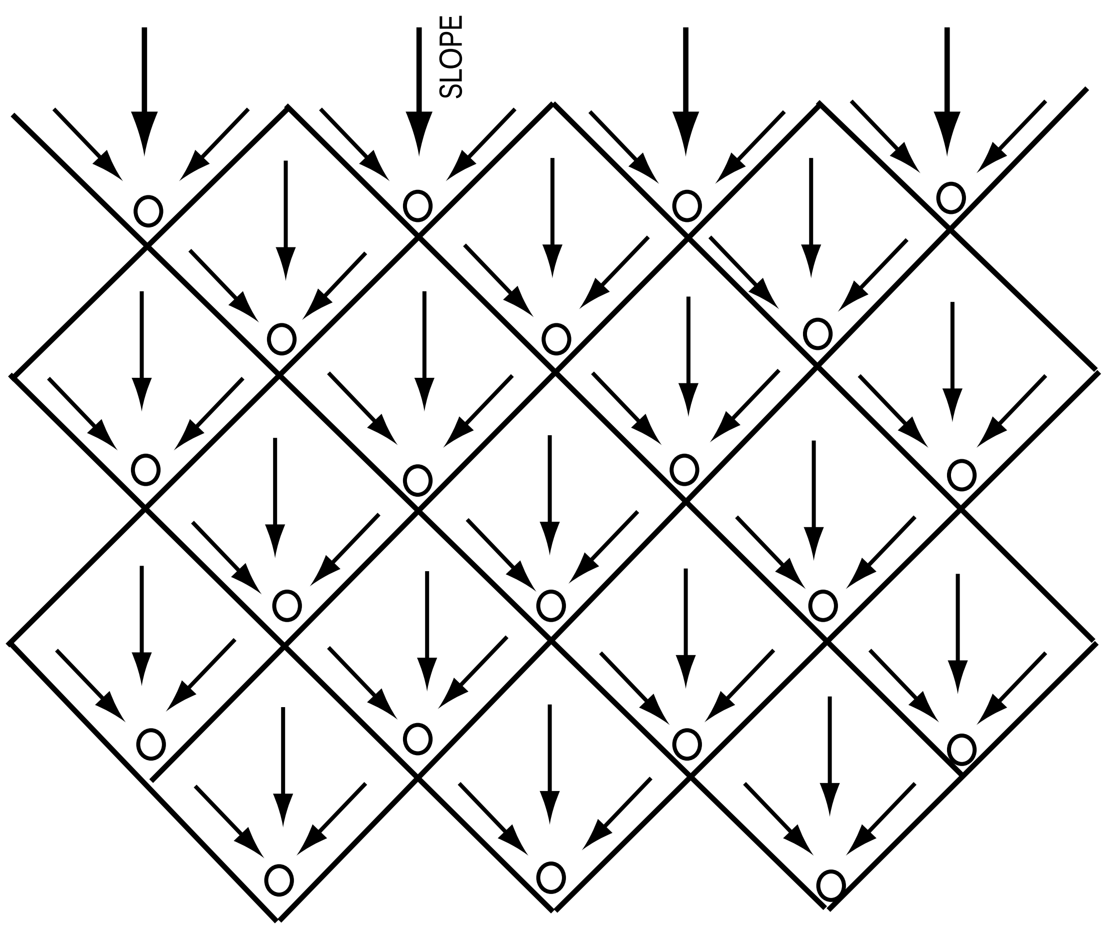


Figure 34. *Negarim microcatchments: Field layout.*

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 or, more usually, an estimate of this. Size of microcatchments (per unit) normally range between 10 m^2 and 100 m^2 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.

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 3 gives recommended figures for different sizes and ground slopes.

vi. Size of infiltration pit

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.

Table 3. *Bund heights (cm) on higher ground slopes*

Size unit microcatchment	Ground slope			
(m^2)	2%	3%	4%	5%
3 × 3	even bund height of 25 cm			
4 × 4				30
5 × 5			30	35
6 × 6			35	45
8 × 8		35	45	55
10 × 12	30	45	55	
12 × 12	35	50	not recommended	
15 × 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.

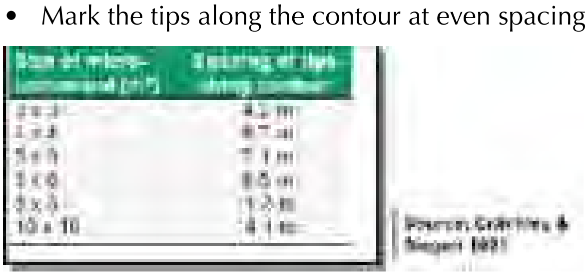
Layout and construction of Negarims

Step One

- Stake out the contour by using a line level or a water tube level
- Smooth contours if required
- If the topography is very uneven, separate blocks of negarims

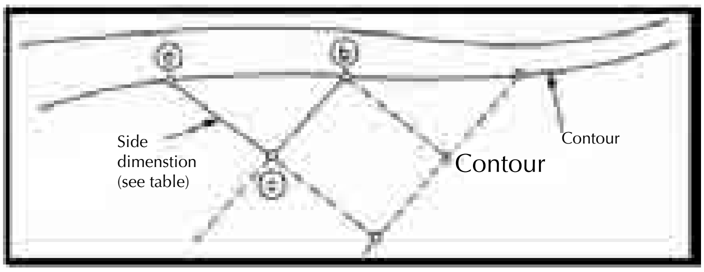
Step Two

- Mark the tips along the contour at even spacing with a tape.



Step Three

- Hold a string from each of both tips of a microcatchment. If held tight, they will meet at the lowest point of the catchment (apex)
- Mark the apex with a peg. Continue until all catchments in the upper row have been marked



Step Four

- Lay out the next lower row :
- The apex of the catchment below is now a tip of the second row
- Repeat Step Three for all further rows

Step Five

- Stake out size and excavate pit

Step Six

- Clear the catchment of all vegetation
- Use the excavated soil from the pit to construct the bunds in two layers
- Wet and compact bund by foot or with a barrel filled with sand or water

Fix a string at the beginning and end of each side of the bund and adjust it above ground at the selected bund height to ensure a uniform height

Step Seven

- Plant tree seedlings of at least 30 cm height after the first rain of the season

It is recommended to plant two seedlings: one in the bottom of the pit and one on a step at the back of the pit.

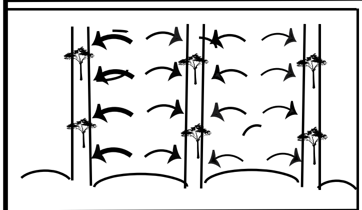
3.1.4 Natural depressions

Natural depressions can also be used for storing water (Figure 35).

Figure 35. *Water harvesting in natural depressions.*

3.1.5 Inter-row water harvesting

INTERROW WATER HARVESTING



>200–500 mm/yr

0–5%

Soil depth > 1 m

Runoff area:

. smoothing
. compaction
. sealing with salts or other sealants
. wedding

= 1–3 m^2

= 0.3–1 m^2

= 1:1 to 5:1

Millet, maize, beans, grapes, olive trees

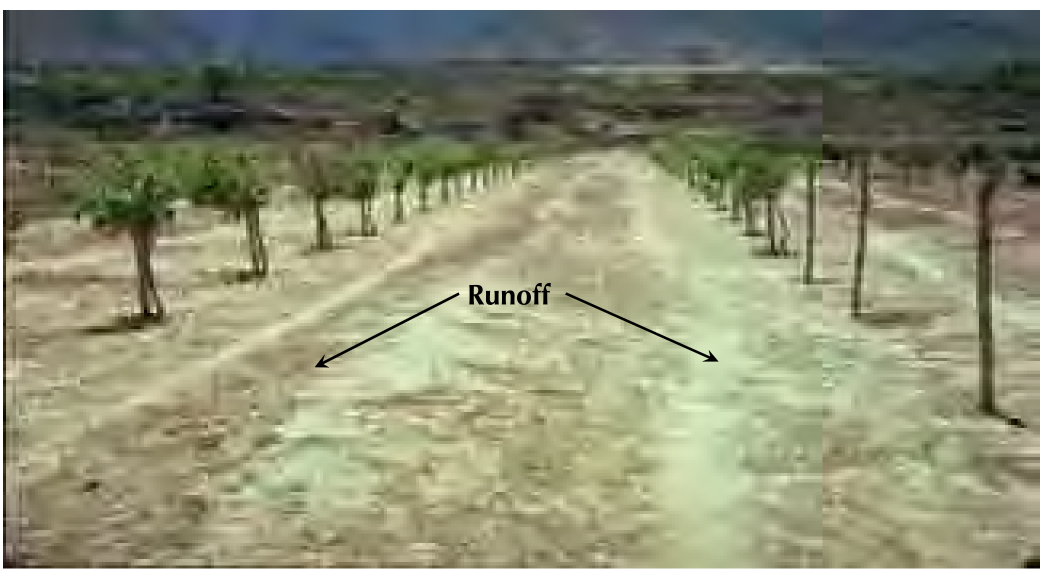


Figure 36. *Inter-row water harvesting.*

CONSTRUCTION :

- (by hand), rollers or tractors

ADVANTAGES :

- can be fully mechanized

LABOUR DEMAND :

- high (if manually implemented)

3.1.6 Contour bench terraces

Typical bench terraces are shown in Figures 37 and 38.

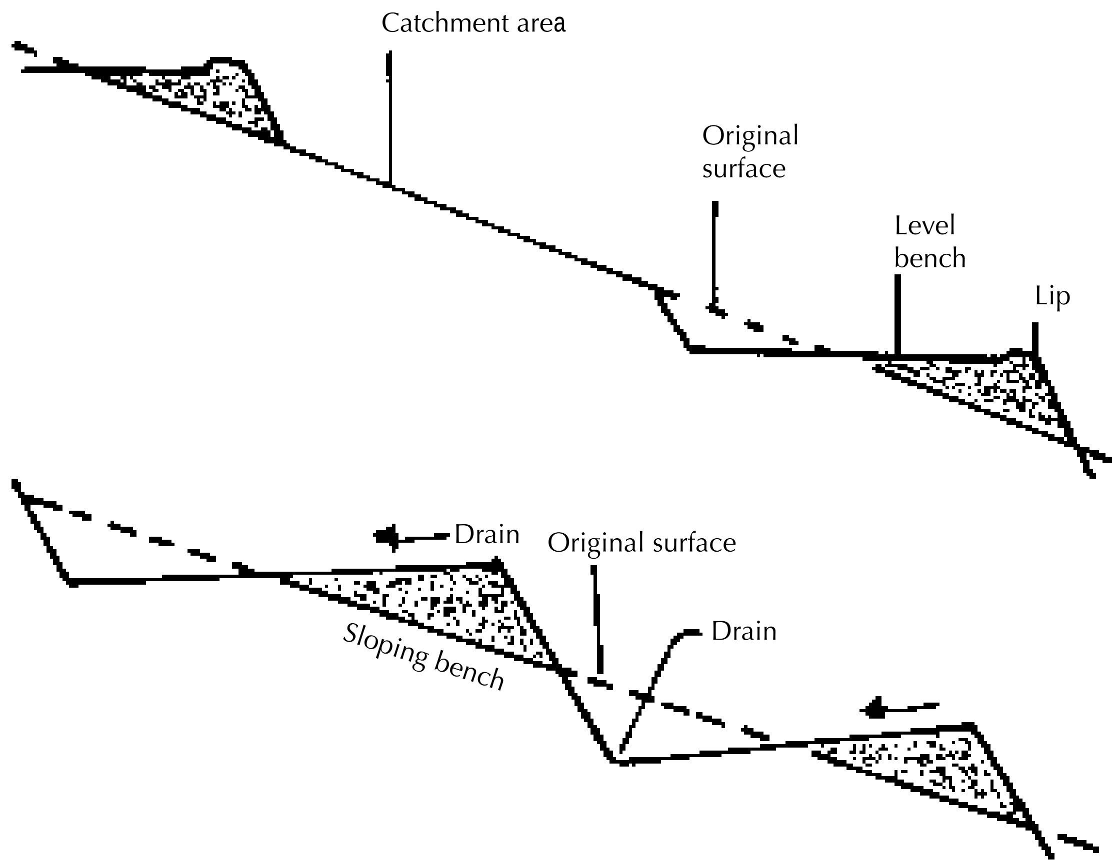


Figure 37. *Different types of contour bench terraces.*

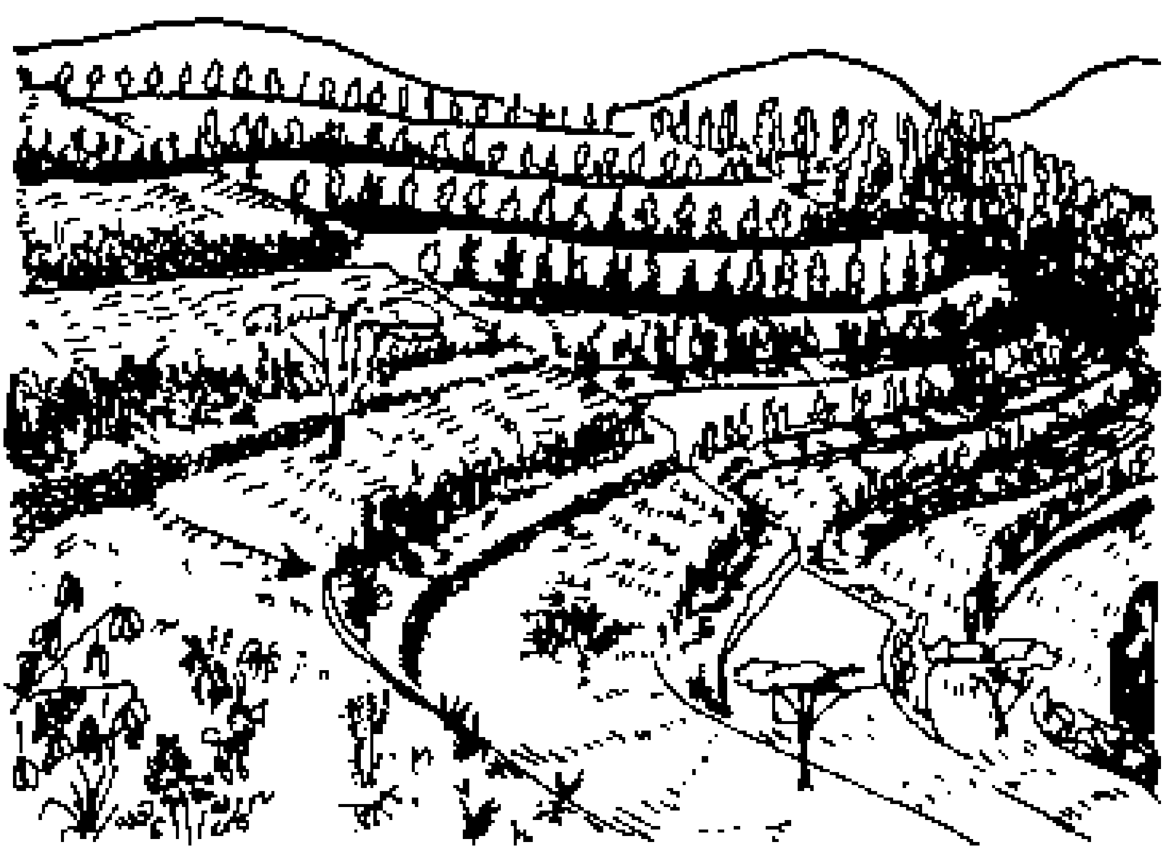


Figure 38. *Contour bench terrace for water harvesting.*

DIMENSIONS:

- strip width depends on slope

CONSTRUCTION (Figure 39):

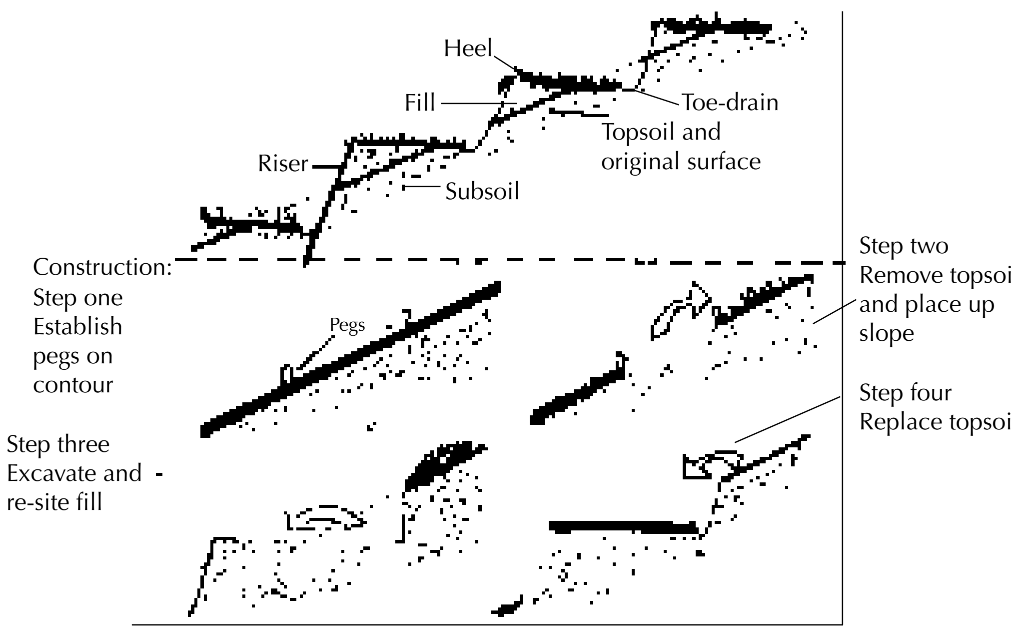
- manual
- by animal
- tractors or bulldozers

LABOUR DEMAND/COST:

- high

LIMITATIONS:

- bare surfaces increase runoff but enhance erosion



Source: Adapted from Rocheleau (1998).
Figure 39. *Construction of terraces.*

3.1.7 Eyebrow terraces

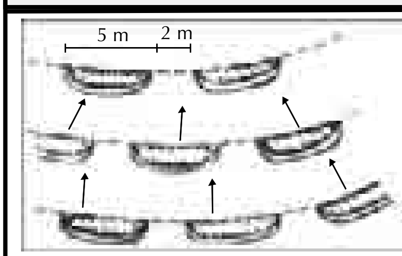
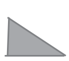
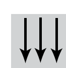
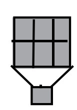
A typical eyebrow terrace is shown in Figure 40.

Figure 40. *Eyebrow terrace.*

Construction (Figure 41)

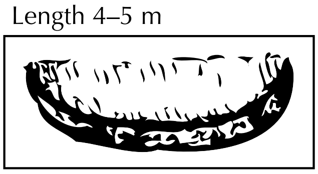
- Dig a pit in the centre of the basin
- Prepare soft earth for planting
- Plant a tree seedling
- Position basins in staggered rows on the contour

Figure 41. *Construction of eyebrow terrace.*

Vallerani-type Microcatchment		
  = 200–600 mm/yr  = 2–10 %	. Microbasins of 600 litres volume . Fully mechanized construction	 = 2–16 m^2  = 2.4 m^2  = 6:1
 Agroforestry, reforestation shelter belts Pasture improvement		

Dimensions:

Length 4–5 m



Width 0.40 m

Depth 0.40 m

3.1.8 Valerian-type micro-catchments

ADVANTAGE:

- Coverage of 10–15 ha/day

DISADVANTAGE:

- high investment costs

Vallerani-type microcatchments are made by the ‘Dolphin-plough’, pulled by a 160–180 hp tractor.

3.1.9 Pits

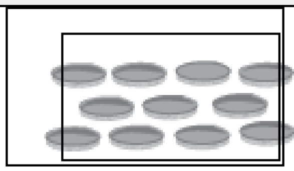
PIT (Burkina Faso: “Zay”)		
 = 350–360 mm/year = < 5%	. dig holes . add manure or composite to increased yield	0.25 m^2 0.08 m^2 3:1
Annual crops, esp. cereals (millet, maize, sorghum) Soil improvement/reclamation		

Figure 42. *‘Zay’ pitting holes.*

DIMENSIONS OF ‘ZAY’:

- depth 5–15 cm
- diameter 10–30 cm
- spacing 50–100 cm

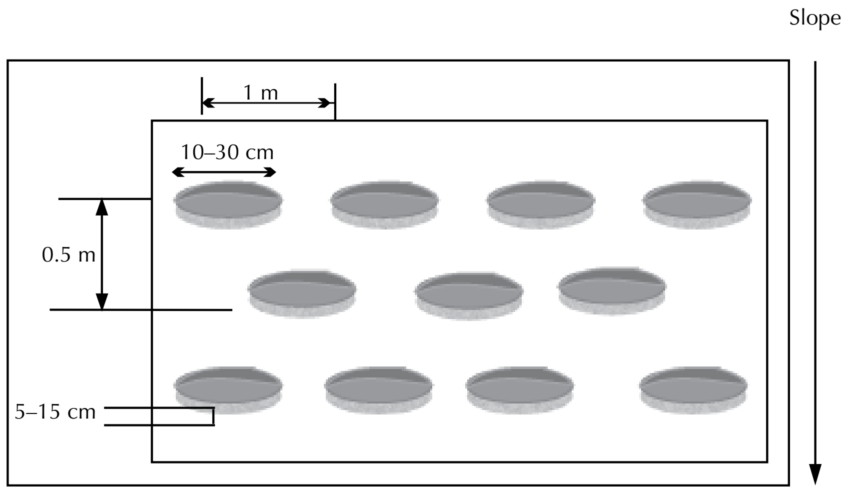


Figure 43. *Dimension of 'Zay'.*

LABOUR DEMAND:

- low for construction

DISADVANTAGE :

- restoration after each tillage necessary

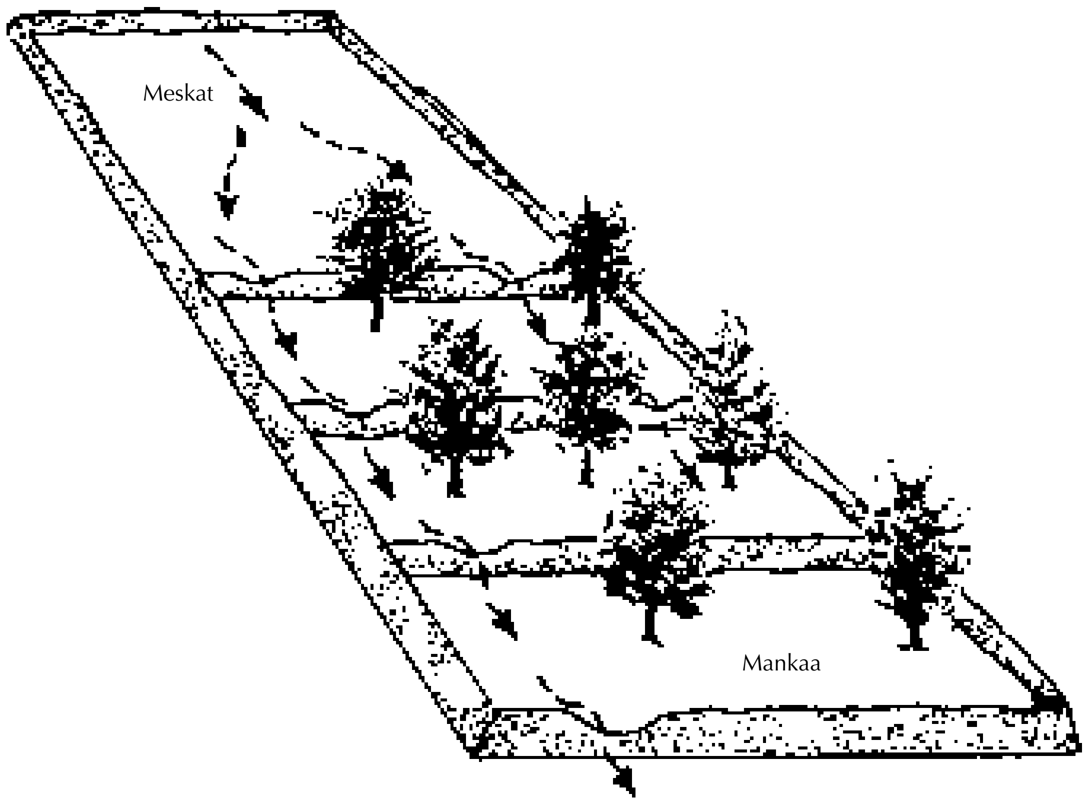
VARIATIONS :

- combination with bunds possible
- dike downslope

3.1.10. Meskat

MESKAT		
= 200–400 mm/yr = 2–15%	. Surrounded by bund . Spillway at upper side of cropping area to let the runoff in	= 500 m^2 = 250 m^2 = 2:1 [2]
Trees (fruit trees, olive trees)		

Figure 44. *Olive plantation in Tunisia. Water from the catchment on the right is directed to the trees (Photo: Mensching).*



Adapted from Reji (1988).
Figure 45. *Tunisian Meskat.*

3.2 Macro-catchments

3.2.1 Stone bunds

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.

Technical details

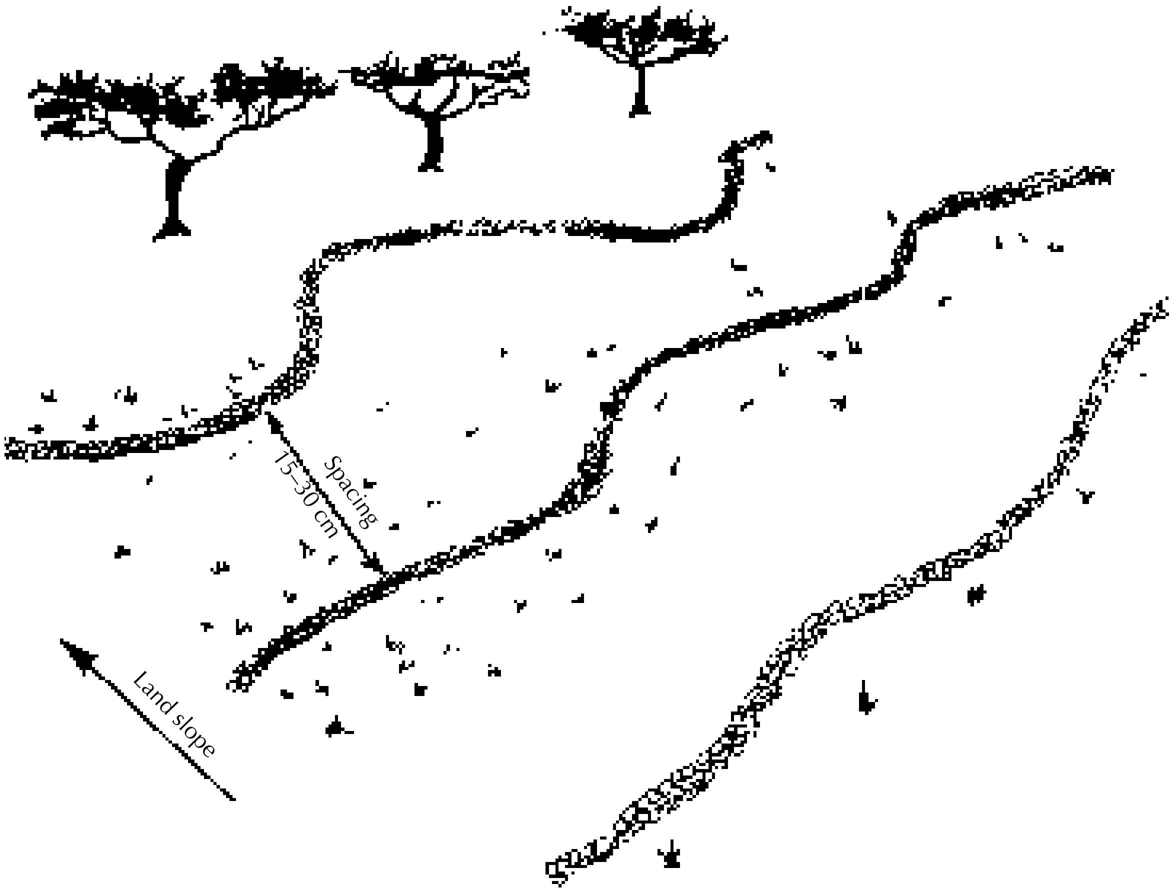
i. Suitability

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 (Figure 46). 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.



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

iii. 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 (Figure 47). 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 spacing of 20 metres for slopes of less than 1%, and 15 metres for slopes of 1–2%, are recommended.

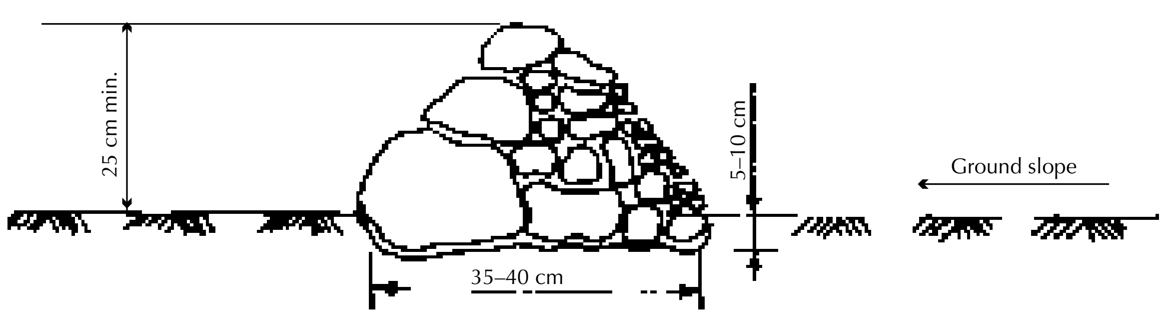


Figure 47. *Contour stone bund: Dimensions.*

Figure 48. *Stone bunds in gentle sloping terrain before rainfall event (Photo: Prinz).*

Figure 49. *Stone bunds in gentle sloping terrain after rainfall event (Photo: Prinz).*

CONSTRUCTION :

- manual

LABOUR DEMAND :

- high (esp. if stones have to be transported by people)

How to build stone bunds

Step One

- Lay out contour, mark and smooth it

Step Two

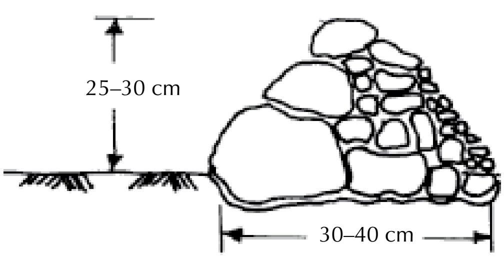
- Dig a shallow foundation trench

Step Three

- Start construction with large stones at the downslope side

Step Four

- Use smaller stones to build rest of the bund. Pack them carefully!
- Pile up earth from trench on upslope side of bund.



Step Five

- Plant *Andropogon* grasses and tree seedlings alongside the bund during the rains

3.2.2 Trapezoidal bunds

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 wing walls which extend upslope at an angle of usually 135°. Crops are planted within the enclosed area. Overflow discharges around the tips of the wing walls.

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 wing walls, 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. The recommended dimensions for one unit of trapezoidal bunds are given in (Figure 50). 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 (Figure 51). However, when planning, it is ok to select other layouts which may fit into the site conditions better. The staggered configuration as shown in Figure 51 should always be followed. It is not recommended to build more than two rows of trapezoidal bunds since those in a third or fourth row receive significantly less runoff.

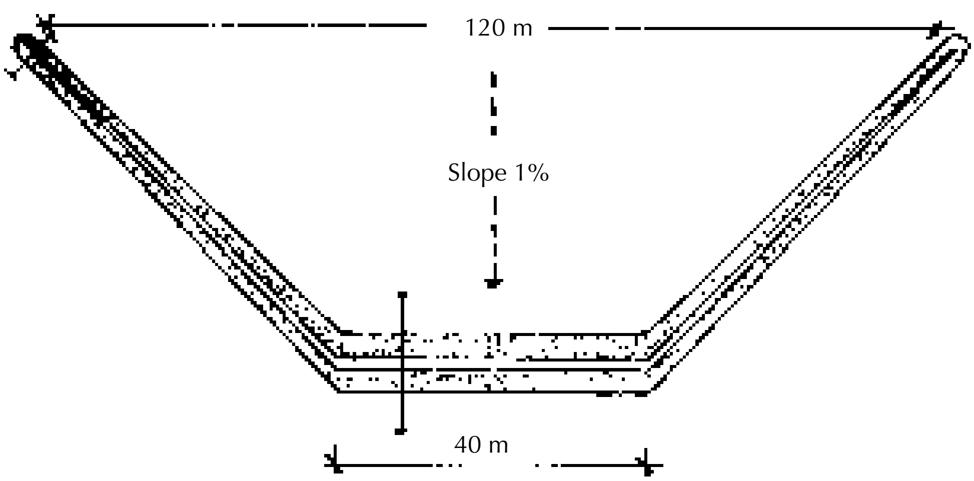


Figure 50. *Trapezoidal bunds dimension of one unit.*

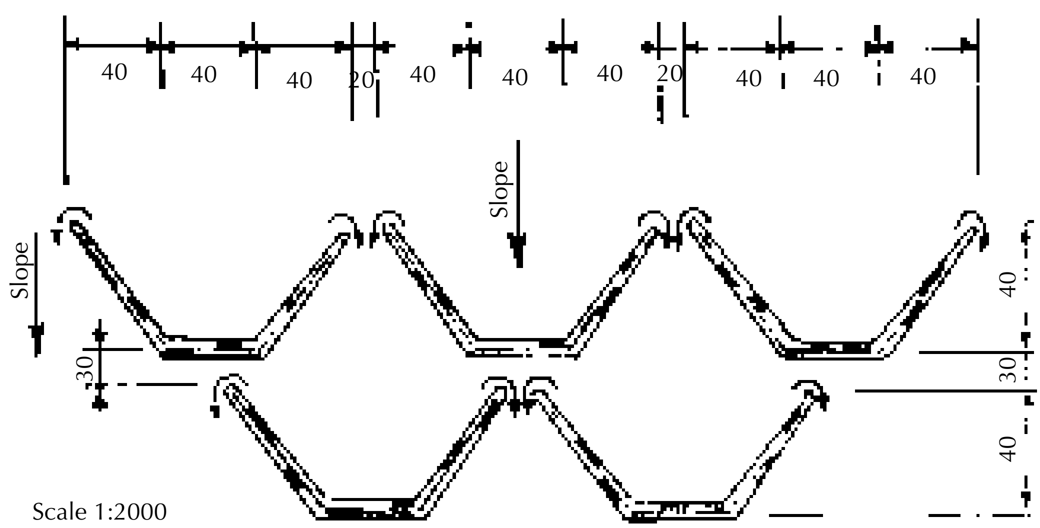


Figure 51. *Trapezoidal bunds: Field layout for 1% ground slope.*

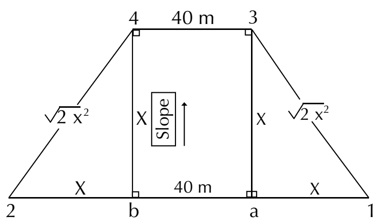
How to lay out and construct trapezoidal bunds

Step One

- Measure slope with Abney level or line level
- Lay out the contour by using a line or water tube level; stake out the tips (points 1+ 2) with a measuring tape and mark them

Step Two

- Measure points a, b, 3 and 4 according to distances



Step Three

- Mark the base width of the bunds and wing walls

Step Four

- Loosen the soil
- Construct bund in two layers, which decrease towards the tips of the wing walls
- Take soil from within the bunded area, where possible
- Wet each layer if possible and compact it thoroughly by rolling, ramming or stamping

Step Five

- Provide bunds with pitched 'lip'

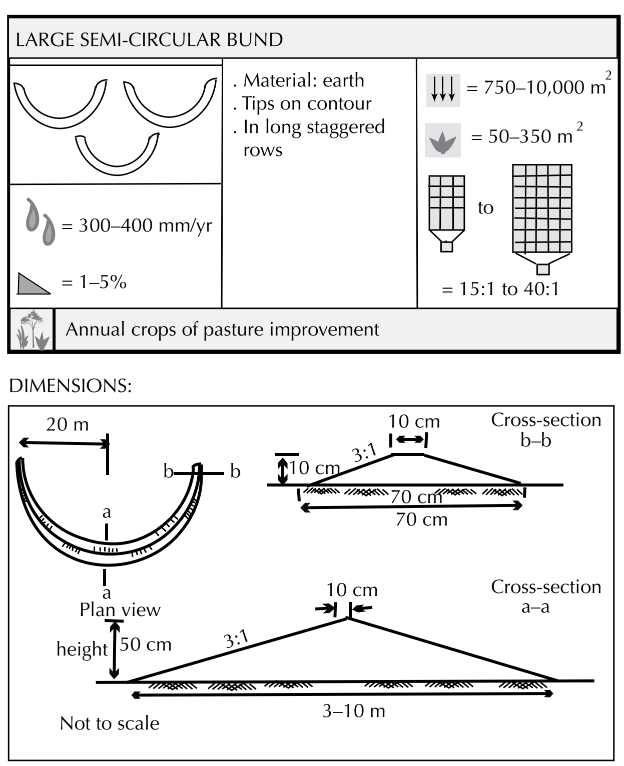


Figure 52. *Dimensions of large semi-circular bunds.*

3.2.3 Large semi-circular bunds

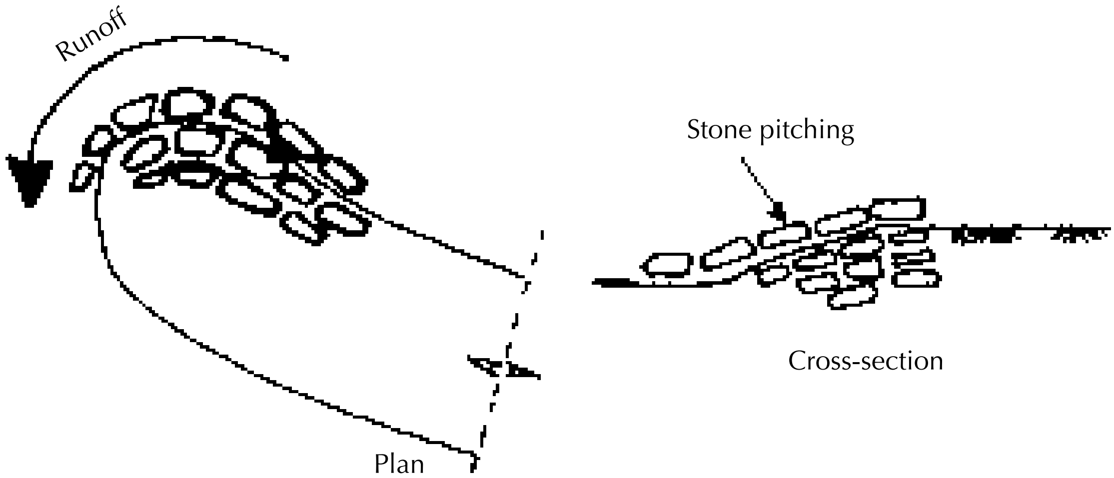


Figure 53. *Wingtip protection.*

3.2.4 Hillside conduit systems

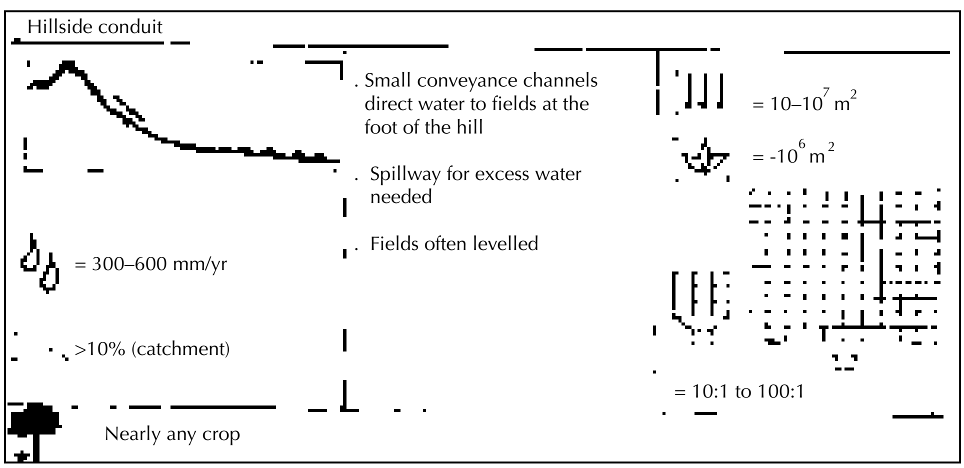


Figure 54. *Water collection area (Photo: Klemm).*

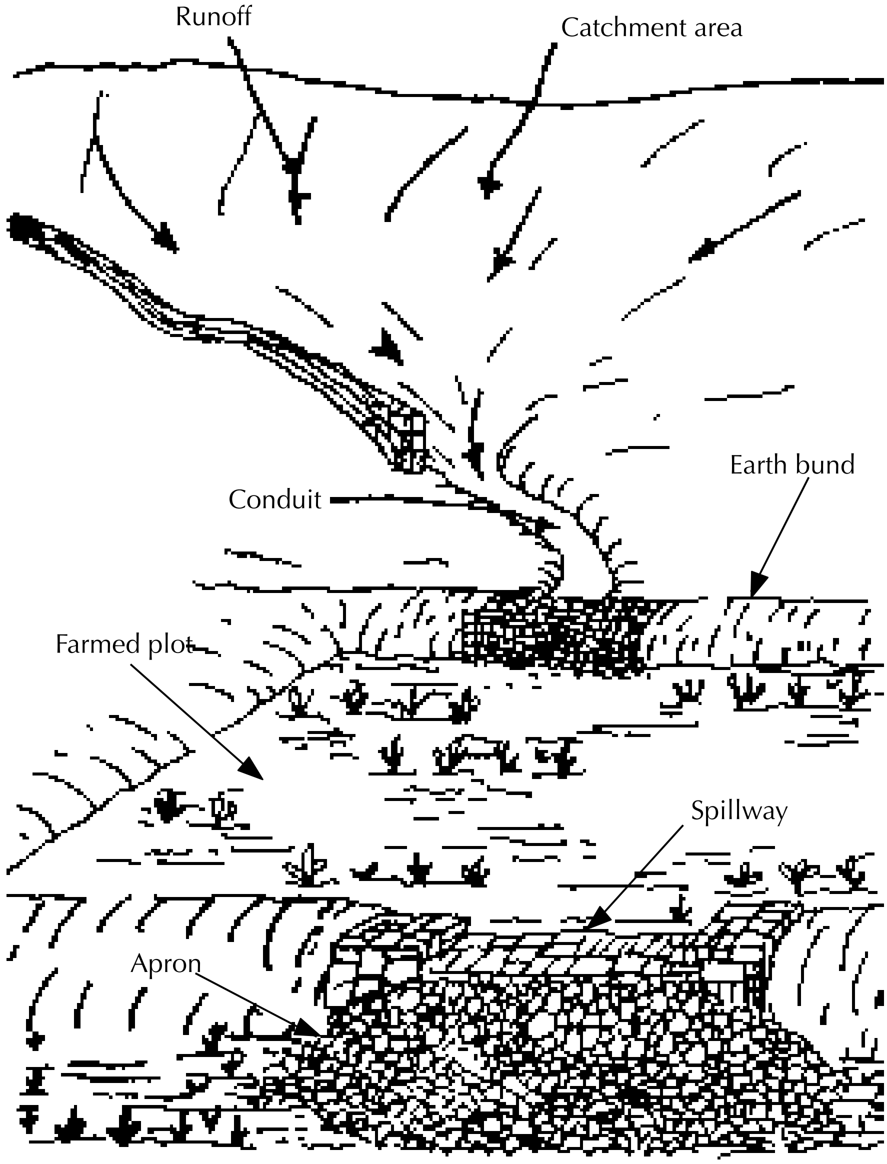


Figure 55. *Hillside conduit system.*

Hillside conduit schemes require proper design, high labour input and probably the assistance of an expert

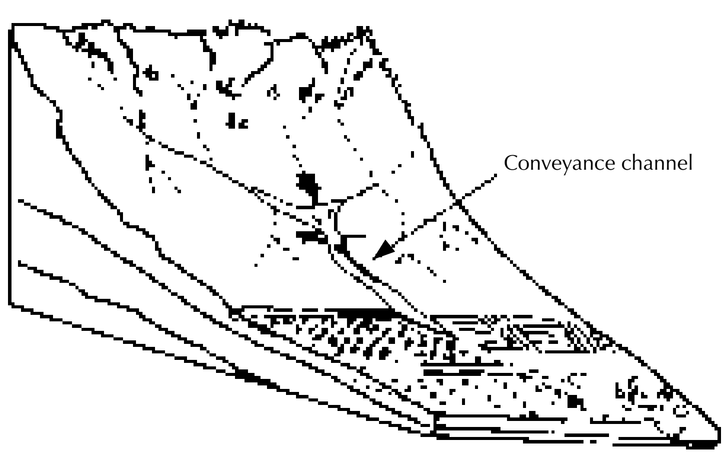


Figure 56. *Typical example of a hillside conduit scheme.*

3.3 Flood harvesting

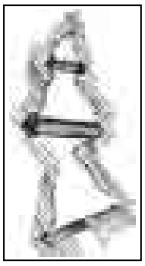
 Minimum rainfall required 150–200 mm/year < 5%	. Cross riverbed check dam in seasonal stream or river . Material: earth, stone or both . Accumulation of sediment . Water infiltration behind dam into sediment . Central spillway or two lateral spillways	Variable (many km^2) = 0.2–5 ha = 100:1 to 10,000:1

Figure 57. *Example of floodwater harvesting.*

DIMENSIONS:

- height : 2–5 m
  (eventually to be increased after some years)
- length : 15–50 m
- width : 4–6 m at base
- spillway at 30–80 cm below dam crest

REQUIRED QUANTITIES OF STONE:
Dependant on slope and spacing of dams

LABOUR DEMAND:

- high

3.3.1 Permeable rock dams

Permeable rock dams are a floodwater farming technique where runoff waters are spread in valley bottoms for improved crop production. Simultaneously developing gullies can be healed. 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.

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 (Figure 58). 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 that 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. Dimensions and construction of the dam is shown in Figure 59.

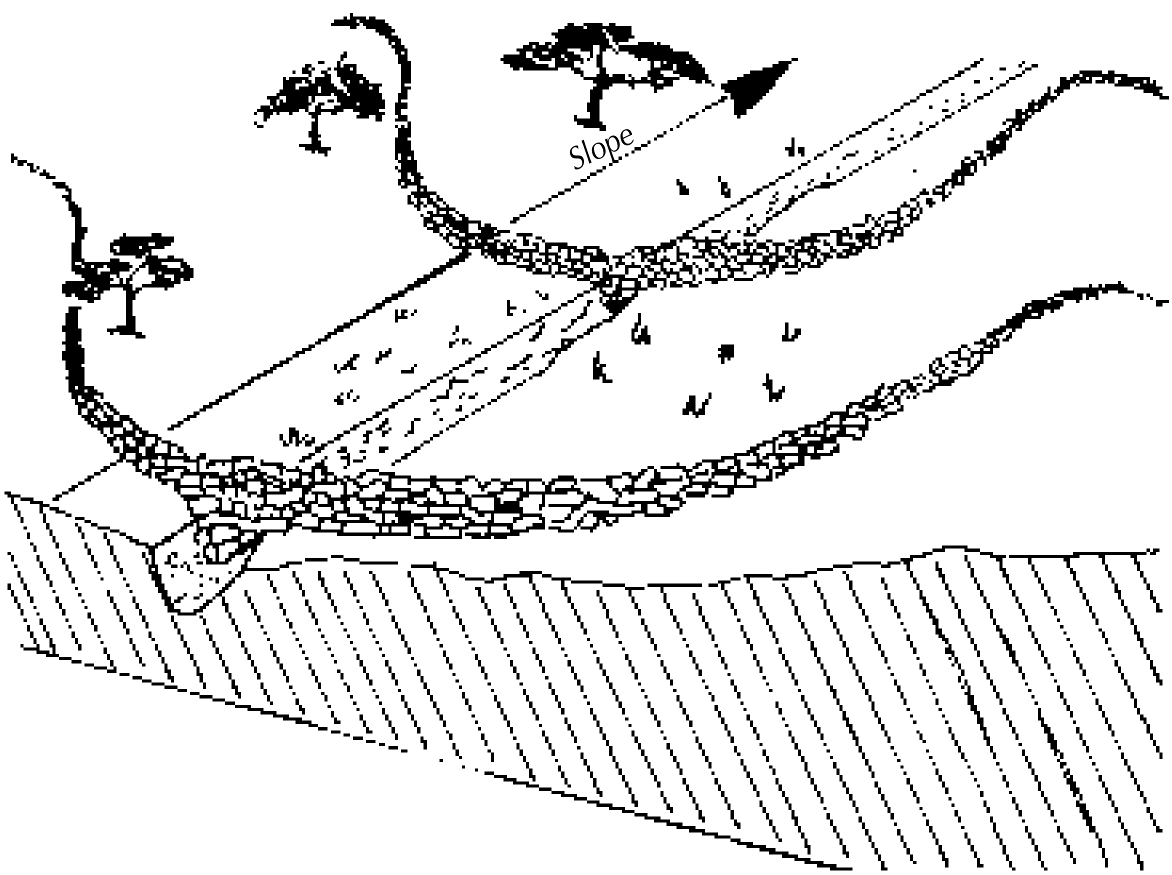


Figure 58. *General layout of permeable rock dams.*

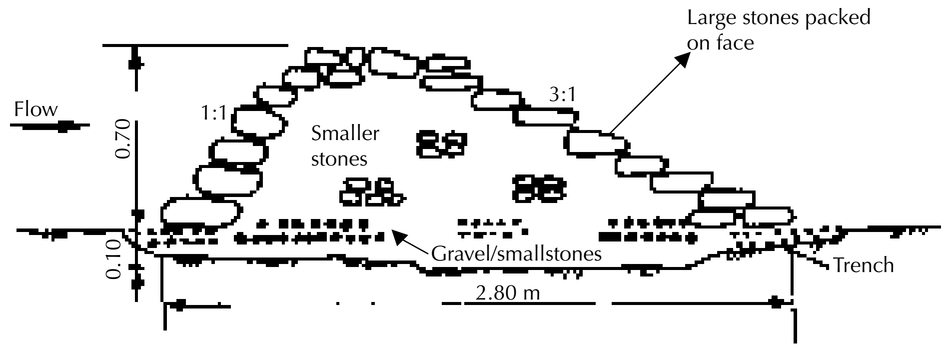


Figure 59. *Dam dimensions.*

3.3.2 Water spreading bunds

The main characteristic of water spreading bunds is that, as their name implies, they are intended to spread water, and not to impound it (Figure 60). 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 60. *Flow diversion system with water spreading bunds.*

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* (ephemeral river channel) 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. 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 down slope is graded from different ends. A short wing wall 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.

3.4 Storage

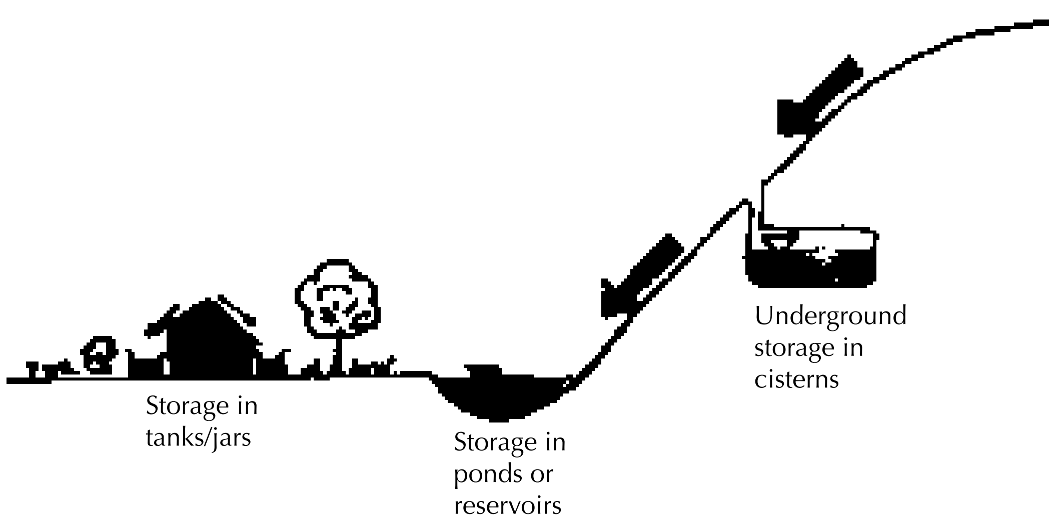


Figure 61. *Roof top water harvesting is mainly used for domestic purposes and gardening.*

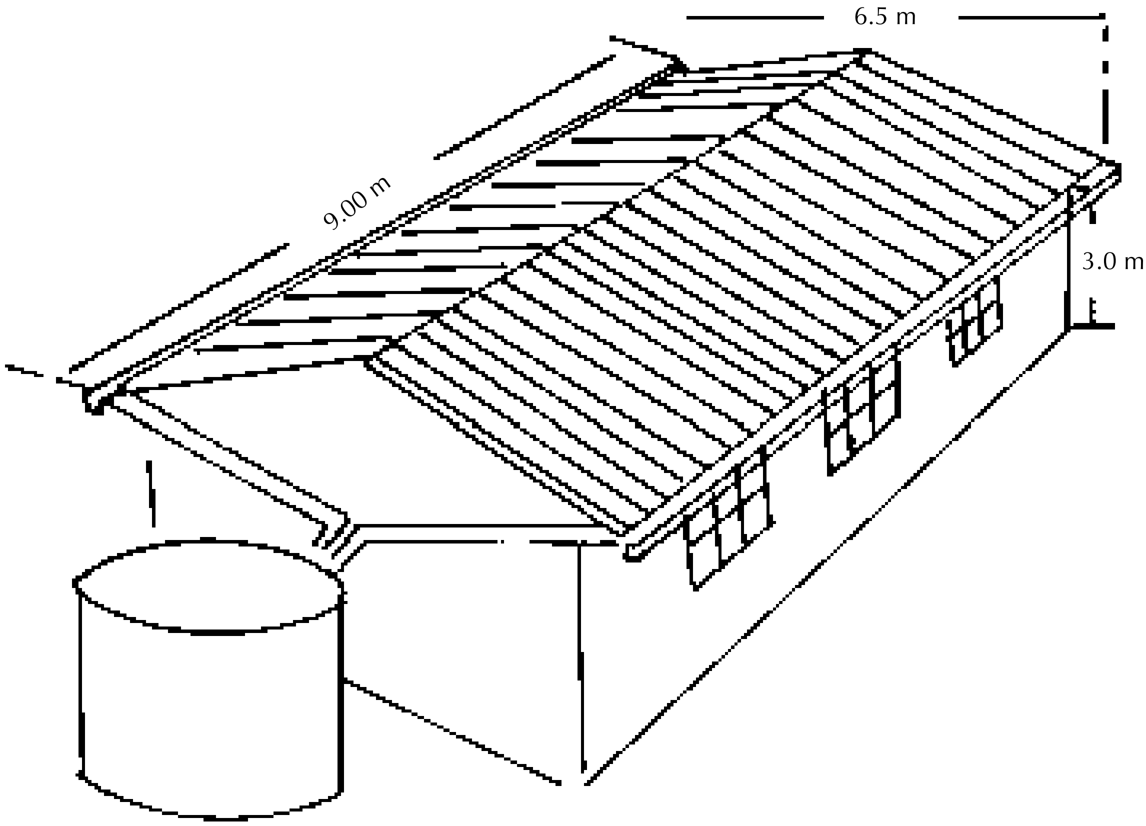


Figure 62. *Storage tank.*

Figure 63. *Typical storage jars.*

Figure 64. *Underground tank of small dimension.*

Catchment tank construction

Step 1: Excavate the hole in a suitable location

- The size will depend on expected water yield and water demand

Step 2: If silt accumulation can be expected, provide a silt trap to arrest the runoff before it is admitted to the storage tank

Step 3: Provide a spillway to evacuate surplus water safely

Step 4: To get the storage tank water-tight, in heavy, alluvial soils, soil compaction might be sufficient; in most soils, lining with brickwork, concrete masonry and cement plaster or with membrane materials will be necessary. Membrane materials are of synthetic rubber, PVC or polyethylene

- Step 5: If technically feasible, the membrane should be protected with concrete armour
- Step 6: Protect the water by constructing a roof, made of thatched material, corrugated iron or other material. To support the roof, build brick pillars if necessary
- Step 7: The catchment tank needs regular cleaning from sediment and debris

Figure 65. *Cistern covered with brush to reduce evaporation; stored water is used for livestock (Somalia) (Photo: Siegert).*

Figure 66. *Pond.*

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Module 3

Soil–plant–water relationships

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Table of Contents

Chapter 1: Soil and water

Objectives:

After understanding this chapter, you will be able to:

- Module 1: Watershed hydrology for improved agricultural water management
- Module 2: Water harvesting and development for improving productivity
- Module 3: Soil –water– plant relationship
- Module 4: Pumps for small scale irrigation
- Module 5: Irrigation methods: Part I: Surface irrigation options for smallholders; Part II: Drip irrigation options for smallholders

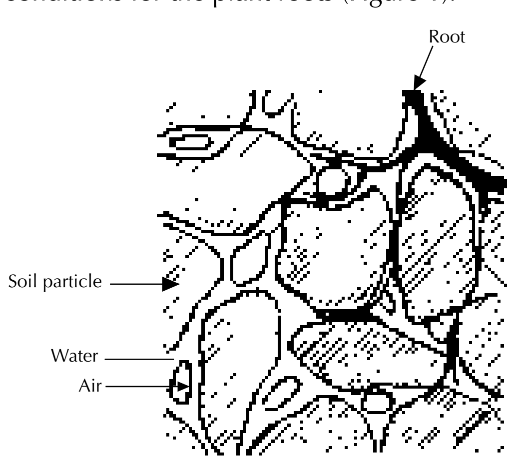
1.1 Introduction

Soil–plant–water relationships are related to the properties of soil and plants that affect the movement and use of water. Soil provides the space for water, which is used by plants through their roots. Water contains a large amount of dissolved nutrients, which are essential for plant growth. If the rainfall is not adequate for plant growth, additional water should be supplied through irrigation. The entry of water into the soil and its retention, movement and availability to plant roots should be known for the efficient management of irrigated agriculture.

1.2 Soil characteristics

1.2.1 Soil composition

When dry soil is crushed in the hand, it can be seen that it is composed of all kinds of particles of different sizes (Hansen et al. 1980; FAO 1985; Garg 1989; Schwab et al. 1993). Most of these particles originate from the degradation of rocks. They are called mineral particles. Some originate from residues of plants or animals (rotting leaves, pieces of bones etc.). These are called organic particles (or organic matter). The soil particles seem to touch each other, but in reality have spaces in between. These spaces are called pores. When the soil is 'dry', the pores are mainly filled with air. After irrigation or rainfall, the pores are mainly filled with water. Living materials are also found in the soil. They can be live roots as well as beetles, worms, larvae etc. They help to aerate the soil and thus create favourable growing conditions for the plant roots (Figure 1).



Source: FAO (1985).
Figure 1. *The composition of the soil.*

Soil profile

If a pit of at least 1 m deep is dug in the soil, various layers, which are different in colour and composition, can be seen. These layers are called horizons. The succession of horizons is called the profile of the soil (Figure 2). A very general and simplified soil profile can be described as follows (USDA 1960; FAO 1985; Murthy 2007):

a. The plough layer (20 to 30 cm thick): is rich in organic matter and contains many live roots. This layer is subject to land preparation (e.g. ploughing, harrowing etc.) and often has a dark colour (brown to black).
b. The deep plough layer: This contains much less organic matter and live roots. This layer is hardly affected by normal land preparation activities. The colour is lighter, often grey, and sometimes mottled with yellowish or reddish spots.
c. The subsoil layer: This has hardly any organic matter or live roots. It is not very important for plant growth, as only a few roots will reach it.
d. The parent rock layer: This one consists of rock, from the degradation of which the soil was formed. This rock is sometimes called parent material.

The depth of the different layers varies widely and some layers may be missing altogether.

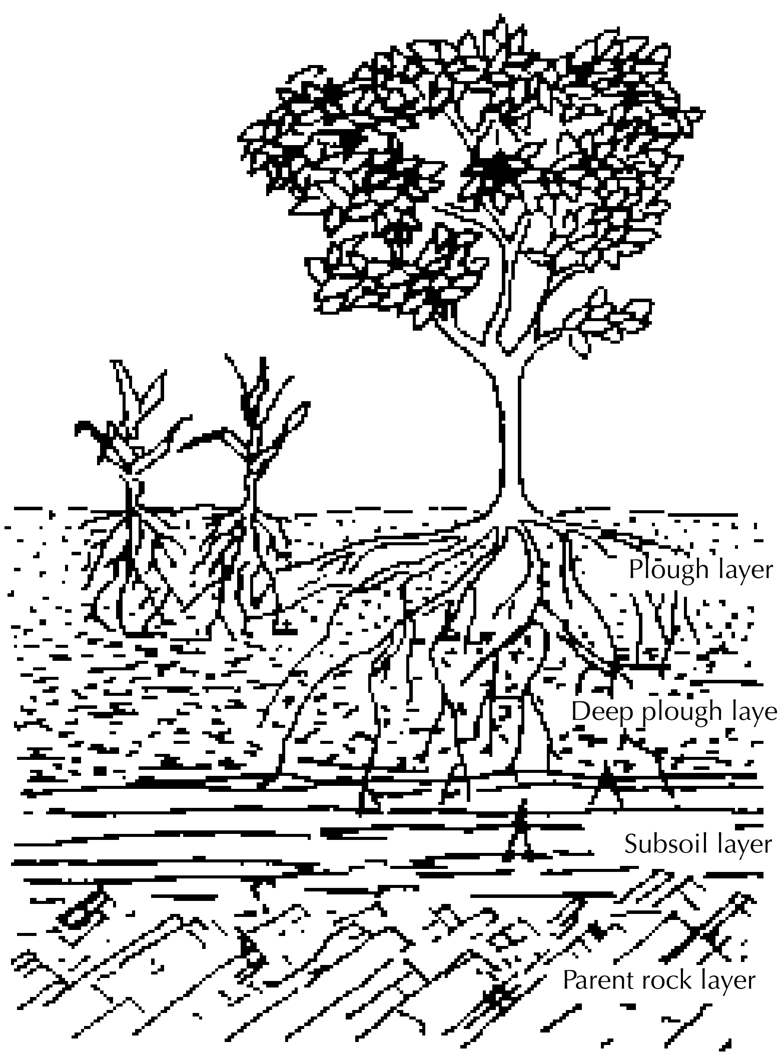


Figure 2. *The soil profile.*

1.2.1 Soil texture

The mineral particles of the soil differ widely in size and can be classified, depending on their size, as gravel, sand, silt and clay (Table 1).

Table 1. *Soil classification*

Name of the particles	Size limits in mm	Distinguishable with naked eye
Gravel	Larger than 1	Obviously
Sand	1 to 0.5	Easily
Silt	0.5 to 0.002	Barely
Clay	less than 0.002	Impossible

The amount of sand, silt and clay present in the soil determines the soil texture.
In coarse textured soils: sand is predominant (sandy soils).
In medium textured soils: silt is predominant (loamy soils).
In fine textured soils: clay is predominant (clayey soils).

In a field, soil texture can be determined by rubbing the soil between the fingers. Farmers often talk of light soil and heavy soil (Table 2). A coarse-textured soil is light because it is easy to work, while a fine-textured soil is heavy because it is hard to work. The texture of a soil is permanent, the farmer is unable to modify or change it.

Table 2. *Expression used by farmers to classify soils*

Expression used by the farmer	Expression used in literature	
Light	Sandy	Coarse
Medium	Loamy	Medium
Heavy	Clayey	Fine

1.2.2 Soil structure

Soil structure refers to the grouping of soil particles (sand, silt, clay, organic matter and fertilizers) into porous compounds (Hansen et al. 1980; Garg 1989; Schwab et al 1993; Murthy 2007). These are called aggregates. Soil structure also refers to the arrangement of these aggregates separated by pores and cracks (Figure 3). The basic types of aggregate arrangements are granular, blocky, prismatic, and massive structures (Figure 4).

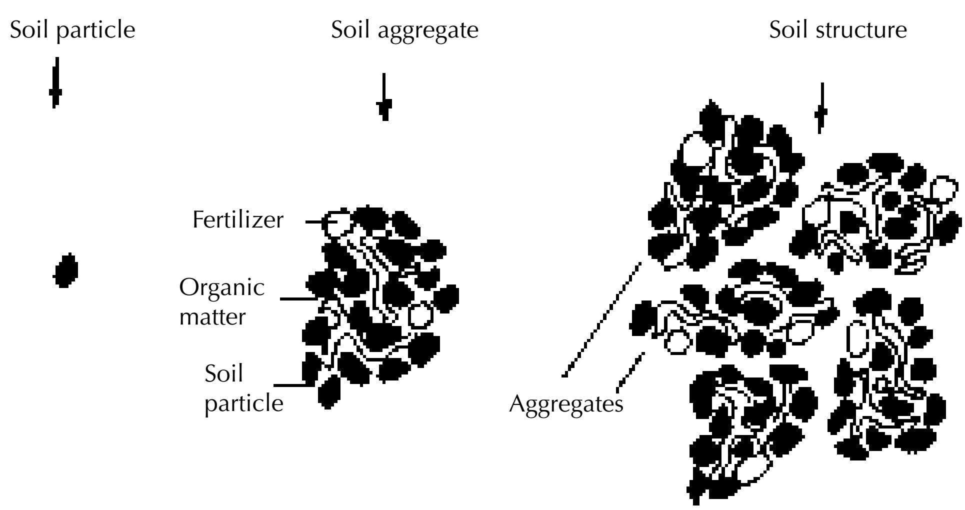


Figure 3. *Soil structure.*

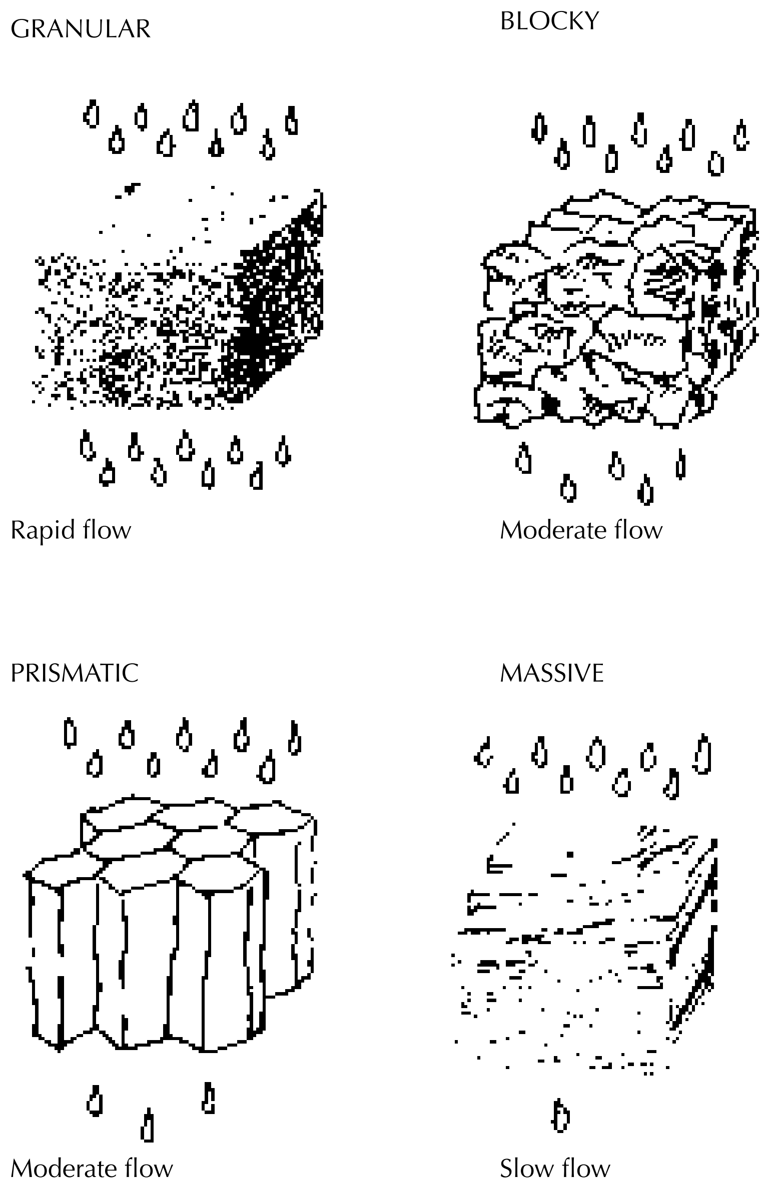


Figure 4. *Some examples of soil structures.*

When present in the topsoil, a massive structure blocks the entrance of water and makes seed germination difficult due to poor aeration. On the other hand, if the topsoil is granular, the water enters easily and the seed germination is better. In a prismatic structure, movement of the water in the soil is predominantly vertical and therefore the supply of water to the plant roots is usually poor. Unlike texture, soil structure is not permanent. By means of cultivation practices (ploughing, ridging etc.), farmers try to obtain a granular topsoil structure for their fields.

1.3 Entry of the water into the soil

1.3.1 Infiltration process

When rain or irrigation water is supplied to a field, it seeps into the soil. This process is called infiltration. The velocity at which water can seep into the soil is called the infiltration rate. It is commonly measured as a depth of the water layer (in mm) that the soil can absorb in an hour (Table 3). An infiltration rate of 15 mm/hour means that a water layer of 15 mm on the surface of the soil will take one hour to infiltrate.

Table 3. *Ranges of values for infiltration rates*

Low infiltration rate	Less than 15 mm/hour
Medium infiltration rate	15 to 50 mm/hour
High infiltration rate	More than 50 mm/hour

Source: FAO (1985).

1.3.2 Factors influencing the infiltration rate

The infiltration rate of a soil depends on factors that are constant, such as the soil texture. It also depends on factors that vary, such as the soil moisture content and the soil structure (FAO 1985; Panda 2005; Murthy 2007).

i. Soil texture

Coarse textured soils have mainly large particles in between which there are large pores. On the other hand, fine textured soils have mainly small particles in between which there are small pores (Figure 5). In coarse soils, the rain or irrigation water enters and moves more easily into larger pores; it takes less time for the water to infiltrate into the soil. Therefore the infiltration rate tends to be higher for coarse textured soils than for fine textured soils.

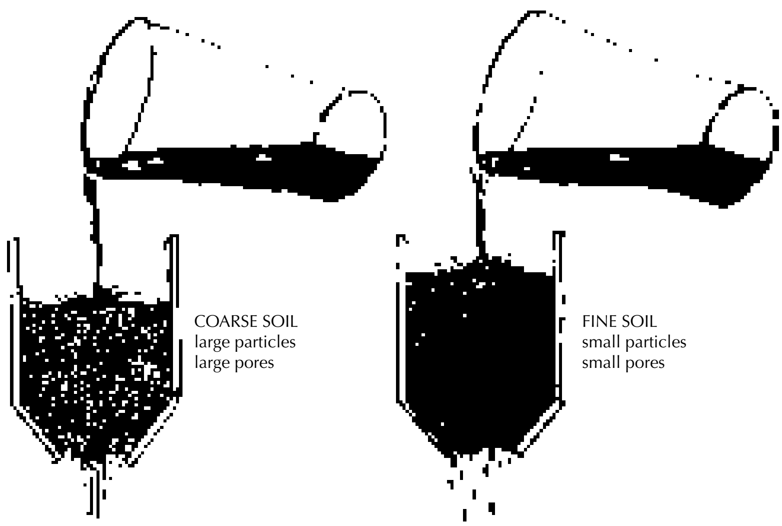


Figure 5. *Infiltration rate and soil texture.*

ii. The soil moisture content

The water infiltrates faster (higher infiltration rate) when the soil is dry, than when it is wet. As a consequence, when irrigation water is applied to a field, the water at first infiltrates easily, but as the soil becomes wet, the infiltration rate decreases.

iii. The soil structure

Generally speaking, water infiltrates quickly (high infiltration rate) into granular soils but very slowly (low infiltration rate) into massive and compact soils.

Because farmers can influence the soil structure (by means of cultivation practices), they can also change the infiltration rate of their soil.

1.4 Soil moisture conditions

1.4.1 Soil moisture content

The soil moisture content indicates the amount of water present in the soil. It is commonly expressed as the amount of water (in mm of water depth) present in a depth of one metre of soil. For example, when an amount of water (in mm of water depth) of 150 mm is present in a depth of one metre of soil, the soil moisture content is 150 mm/m. The soil moisture content can also be expressed in percent of volume. In the example above, 1 m^3 of soil (e.g. with a depth of 1 m, and a surface area of 1 m^2) contains 0.150 m^3 of water (e.g. with a depth of 150 mm = 0.150 m and a surface area of 1 m^2). This results in soil moisture content in volume percent (FAO 1985):

$$\frac{0.150\ m^3}{1 m^3} \times 100\ \% = 15\%$$

Thus, a moisture content of 100 mm/m corresponds to moisture content of 10 volume percent.

The amount of water stored in the soil is not constant but may vary.

1.4.2 Saturation

During a rain shower or irrigation application, the soil pores will fill with water. If all soil pores are filled with water, the soil is saturated (FAO 1985; Panda 2005; Murthy 2007). There is no air left in the soil (Figure 6a). It is easy to determine in the field if a soil is saturated. If a handful of saturated soil is squeezed, some (muddy) water will run between the fingers. Plants need air and water in the soil. At saturation, no air is present and the plant will suffer. Many crops cannot withstand saturated soil conditions for a period of more than 2–5 days. Rice is one of the exceptions to this rule. The period of saturation of the topsoil usually does not last long. After the rain or the irrigation has stopped, part of the water present in the larger pores will move downward. This process is called drainage or percolation. The water drained from the pores is replaced by air. In coarse textured (sandy) soils, drainage is completed within a period of a few hours. In fine textured (clayey) soils, drainage may take some (2–3) days.

1.4.3 Field capacity

After the drainage has stopped, the large soil pores are filled with both air and water while the smaller pores are still full of water. At this stage, the soil is said to be at field capacity. At field capacity, the water and air contents of the soil are considered to be ideal for crop growth (see Figure 6b).

1.4.4 Permanent wilting point

The water stored in the soil is slowly taken up by the plant roots or evaporated from the topsoil into the atmosphere. If no additional water is supplied to the soil, it gradually dries out. The dryer the soil becomes, the more tightly the remaining water is retained and the more difficult it is for the plant roots to extract it. At a certain stage, the uptake of water is not sufficient to meet the plant's needs. The plant loses freshness and wilts and the leaves change colour from green to yellow. Finally the plant dies. The soil water content at the stage where the plants die is called permanent wilting point. The soil still contains some water, but it is too difficult for the roots to suck it from the soil (see Figure 6c).

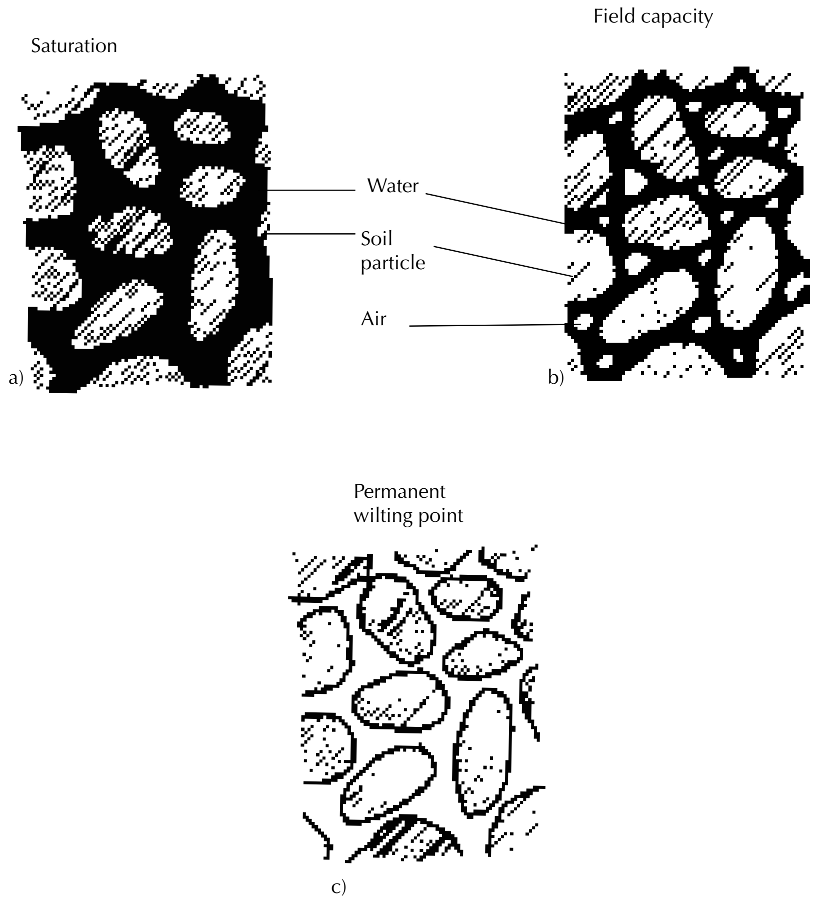
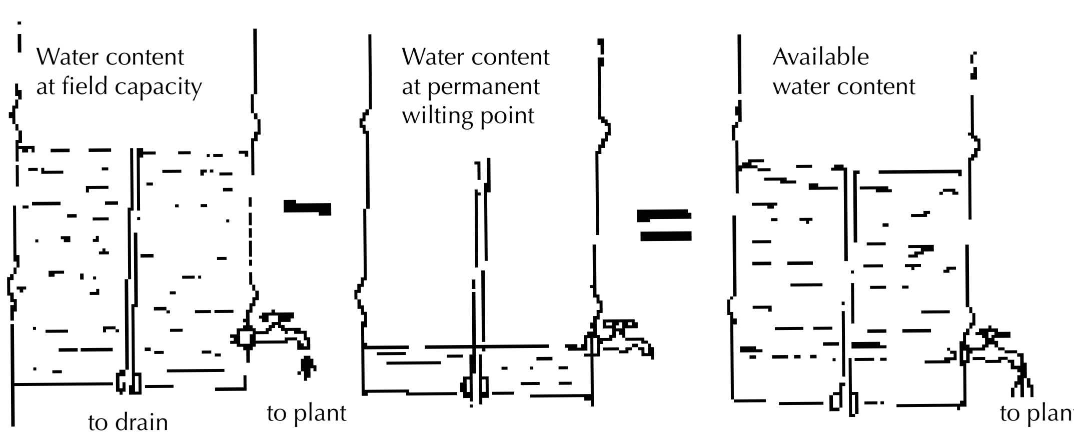


Figure 6. *Some soil moisture characteristics.*

1.4.5 Available water content

Soil can be compared to a water reservoir for the plants. When the soil is saturated, the reservoir is full. However, some water drains rapidly below the root zone before the plant can use it. When this water has drained away, the soil is at field capacity. The plant roots draw water, which remains in the reservoir. When the soil reaches permanent wilting point, the remaining water is no longer available to the plant. The amount of water actually available to the plant is the amount of water stored in the soil at field capacity minus the water that will remain in the soil at permanent wilting point (see Figure 7).



Source: FAO (1985).
Figure 7. *The available soil moisture or water content.*

Available water content = water content at field capacity – water content at permanent wilting point.

The available water content depends greatly on the soil texture and structure. A range of values for different types of soil is given in Table 4.

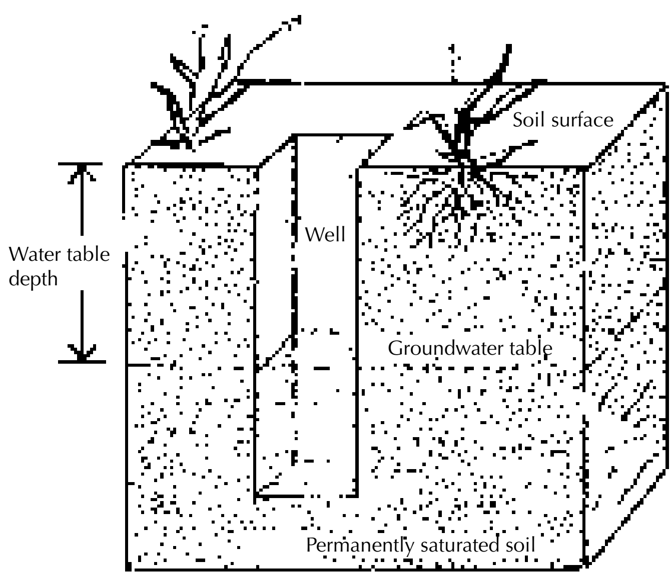
Table 4. *Available water content in the soil*

Soil	Available water content in mm water depth per m soil depth (mm/m)
Sand	25 to 100
Loam	100 to 175
Clay	175 to 250

The field capacity, permanent wilting point (PWP) and available water content are called the soil moisture characteristics. They are constant for a given soil, but vary widely from one type of soil to another.

1.5 Groundwater table

Part of the water applied to the soil surface drains below the root zone and feeds deeper soil layers, which are permanently saturated; the top of the saturated layer is called groundwater table or sometimes just water table (see Figure 8).



Source: FAO (1985).
Figure 8. *The groundwater table*.

1.5.1 Depth of the groundwater table

The depth of the groundwater table varies greatly from place to place, mainly due to changes in topography of the area (see Figure 9). In one particular place or field, the depth of the groundwater table may vary in time. Following heavy rainfall or irrigation, the groundwater table rises. It may even reach and saturate the root zone. If prolonged, this situation can be disastrous for crops, which cannot resist 'wet feet' for a long period. Where the groundwater table appears at the surface, it is called an open groundwater table. This is the case in swampy areas. The groundwater table can also be very deep and distant from the root zone, for example following a prolonged dry period. To keep the root zone moist, irrigation is then necessary.

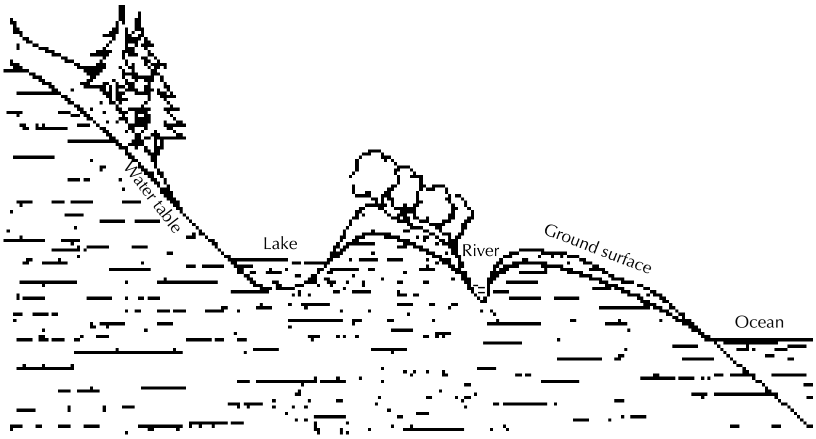


Figure 9. *Variations in depth of the groundwater table.*

1.5.2 Perched groundwater table

A perched groundwater layer can be found on top of an impermeable layer rather close to the surface (20 to 100 cm). It usually covers a limited area. The top of the perched water layer is called the perched groundwater table. An impermeable layer separates the perched groundwater layer from the more deeply located groundwater table (see Figure 10). Soil with an impermeable layer not far below the root zone should be irrigated with precaution, because in the case of over-irrigation (too much irrigation), the perched water table may rise rapidly.

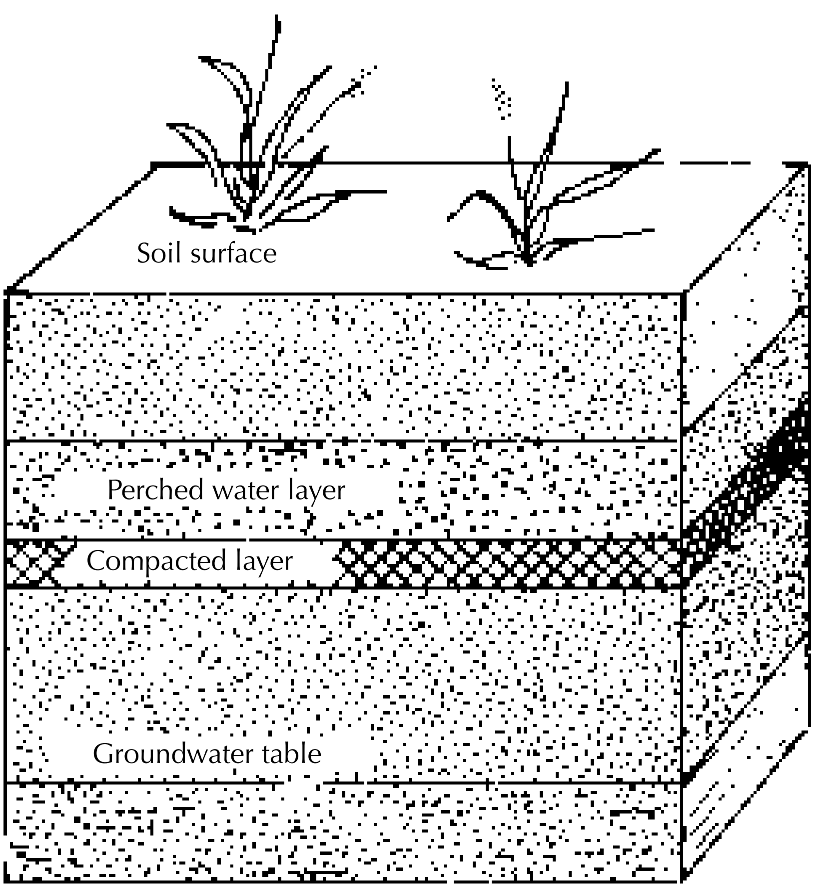


Figure 10. *A perched groundwater table.*

1.5.3 Capillary rise

So far, it has been explained that water can move downward, as well as horizontally or laterally through the soil (Panda 2005). In addition, water can move upward. If a piece of tissue is dipped in water, the water is sucked upward by the tissue. The same process happens with a groundwater table and the soil above it. The groundwater can be sucked upward by the soil through very small pores that are called capillary. This process is called capillary rise. In fine textured soil (clay), the upward movement of water is slow but covers a long distance (Table 5). On the other hand, in coarse textured soil (sand), the upward movement of the water is quick but covers only a short distance.

Table 5. *Capillary rise in different soils*

Soil texture	Capillary rise (in cm)
Coarse (sand)	20 to 50 cm
Medium	50 to 80 cm
Fine (clay)	More than 80 cm up to several metres

Chapter 2: Crop water needs

Objectives

Upon completion of this chapter, you will be able to:

- describe the influences of climate, crop type and growth stage on crop water need.
- explain evapotranspiration
- determine crop water need
- estimate effective rainfall
- determine irrigation water need

All field crops need soil, water, air and light (sunshine) to grow. The soil gives stability to the plants; it also stores the water and nutrients, which the plants can take up through their roots. The sunlight provides the energy, which is necessary for plant growth (Figure 11). The air allows the plants to 'breath'.

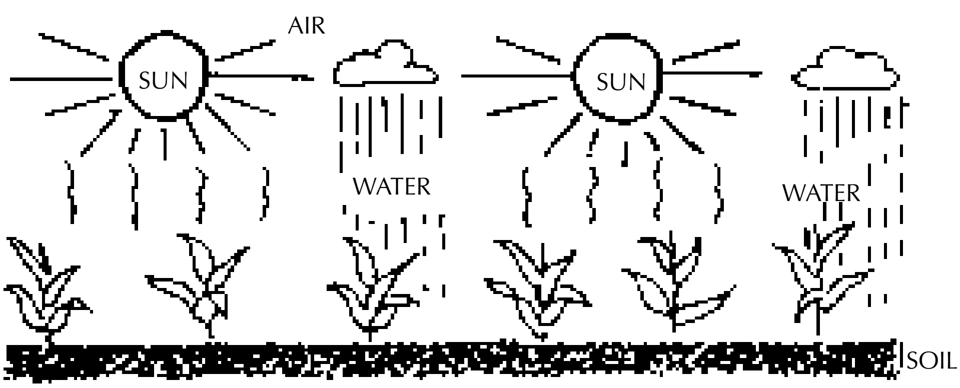


Figure 11. *Plants need soil, water, air and sunlight.*

Without water crops cannot grow. Too much water is not good for many crops either. Apart from paddy rice, there are only very few crops which like to grow 'with their feet in the water'. The most well known source of water for plant growth is rainwater. There are two important questions regarding rainwater that need to be addressed: What to do if there is too much rainwater? What to do if there is too little rainwater? If there is too much rain, the soil will be full of water and there will not be enough air. Excess water must be removed. The removal of excess water—either from the ground surface or from the root zone—is called **drainage**. If there is too little rain, water must be supplied from other sources, i.e. **irrigation** is needed. The amount of irrigation water needed depends, not only on the amount of water already available from rainfall, but also on the total amount of water needed by the various crops.

With respect to the need for irrigation water, a distinction can be made among three climatic situations (FAO 1985):

1. Humid climates: more than 1200 mm of rain per year. The amount of rainfall is sufficient to cover the water needs of the various crops. Excess water may cause problems for plant growth and thus drainage is required.
2. Subhumid and semi-arid climates: between 400 and 1200 mm of rain per year. The amount of rainfall is important but often not sufficient to cover the water needs of the crops. Crop production in the dry season is only possible with irrigation, while crop production in the rainy season may be possible but unreliable: yields will be less than optimal.

3. Semi-arid, arid and desert climates: less than 400 mm of rain per year. Reliable crop production based on rainfall is not possible; irrigation is thus essential.

The two major factors, which determine the amount of irrigation water that is needed, are: (a) total water needs of the various crops, (b) amount of rainwater, which is available to the crops. In other words, the irrigation water needed is the difference between the total water need of the crops and the amount of rainfall, which is available to the crops.

Water needs are the sum of crops transpiration and soil evaporation. The plant roots suck or extract water from the soil to live and grow. Almost all this water does not remain in the plant, but escapes to the atmosphere as vapour through the plant's leaves and stem. This process is called **transpiration**. Transpiration happens mainly during the daytime. Water escapes from an open water surface as vapour to the atmosphere during the day. The same happens to water on the soil surface and free water on the leaves and stem of a plant. This process is called **evaporation**. The water need of a crop thus consists of transpiration plus evaporation. This crop water need is also called '**evapotranspiration**' (Blaney and Criddle 1950; Doorenbos and Pruitt 1975; FAO 1975). The water need of a crop is usually expressed in mm/day, mm/month or mm/season.

Suppose the water need of a certain crop is 6 mm/day. This means that each day the crop needs a water layer of 6 mm over the whole area on which the crop is grown. It does **not** mean that this 6 mm has to be supplied by rain or irrigation every day. It is, of course, still possible to supply 50 mm of irrigation water every 5 days. The irrigation water will then be stored in the root zone and gradually be used by the plants, every day (10 mm). For one hectare, a water layer of 10 mm = 0,010 m X 10,000 m^2 = 100 m^3

1 mm of water = 10 m^3/ha

The crop water need mainly depends on:

The climate:	For example, in a sunny and hot climate crops need more water per day than in a cloudy and cool climate
The crop type:	Crops like rice or sugarcane need more water than crops like beans and wheat
The growth stage:	Grown crops need more water than crops that have just been planted

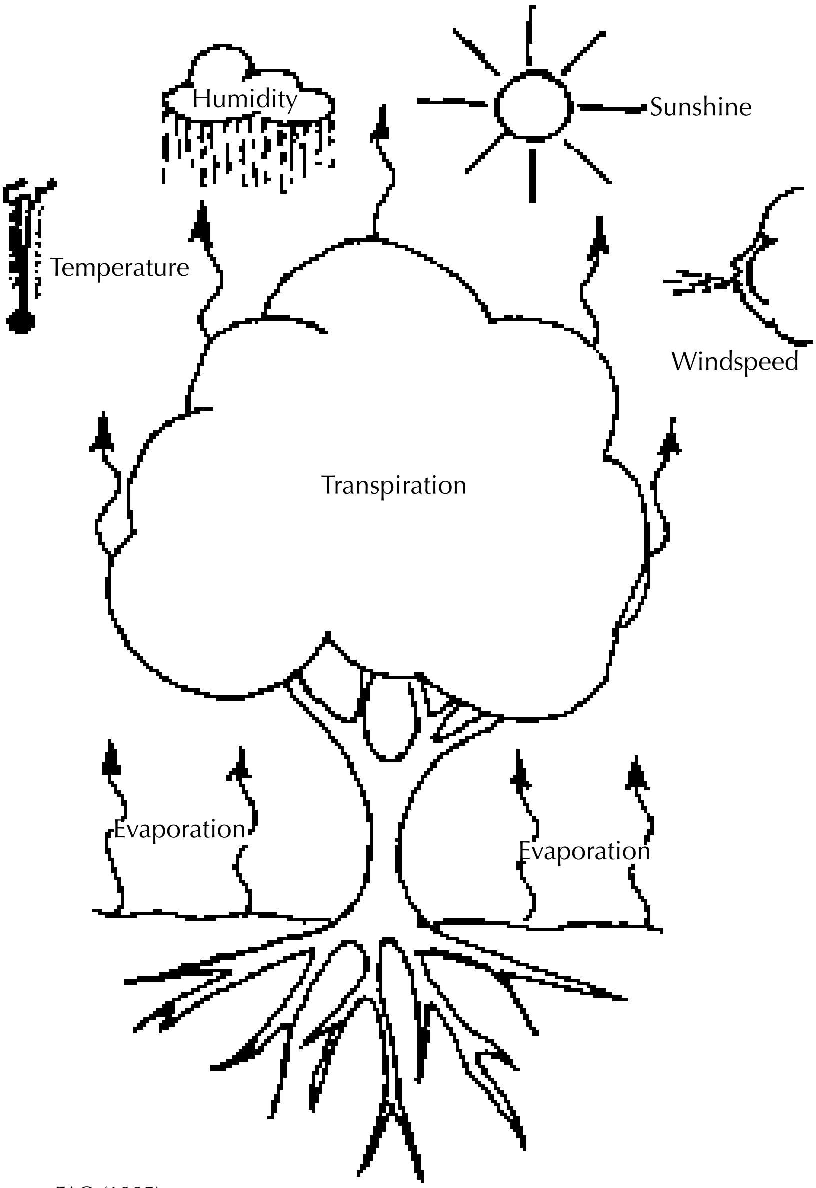
2.1 Influence of climate on crop water needs

A certain crop grown in a sunny and hot climate needs per day more water than the same crop grown in a cloudy and cooler climate. There are, however—apart from sunshine and temperature—other climatic factors that influence the crop water need. These factors are the humidity and the wind speed (Figure 12). 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 effect of these four climatic factors on the water need of the crop is shown in Table 6.

Table 6. *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

Source: FAO (1985).



Source: FAO (1985).
Figure 12. *Major climatic factors influencing crop water needs.*

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 one 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 7 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.

For example, the standard grass crop grown in a semi-arid climate with a mean temperature of 20°C needs approximately 6.5 mm of water per day. The same grass crop grown in a subhumid climate with a mean temperature of 30°C needs some 7.5 mm of water per day. This daily water need of the standard grass crop is also called 'reference crop evapotranspiration'. Most meteorological stations can calculate reference crop evapotranspiration from meteorological data and using formulas such as the

Penman formula. What will be discussed in the next section is 'how do the water needs of the crops grown on, for example, an irrigation scheme relate to the water need of the standard grass'.

Table 7. *Average daily water need of standard grass during irrigation season*

Climatic zone	Mean daily temperature (mm/day)		
	Low	Medium	High
	(Less than 15°C)	(15–25°C)	(More than 25°C)
Desert/arid	4–6	7–8	9–10
Semi-arid	4–5	6–7	8–9
Subhumid	3–4	5–6	7–8
Humid	1–2	3–4	5–6

2.2 Influence of crop type on the crop water needs

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

1. The crop type has an influence on the daily water needs of a fully grown crop, i.e. a fully developed maize crop will need more water per day than a fully developed crop of onions.
2. 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 duration of the total growing season of 90–100 days and longer duration crops, e.g. melons, with duration of the total growing season of 120–160 days. And then there are, of course, the 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 peas, 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. The influences of the crop type on both the daily and seasonal crop water needs are discussed in the sections below.

2.2.1 Influence of crop type on daily crop water needs

In the previous section it has been indicated how the daily water need of standard grass is estimated. In this section it will be explained how the daily water needs of other crops can be estimated using as a basis the daily water need of the standard grass. It will be easy to understand that a fully grown maize crop—with its large leaf area—will use more water per day than, for example, a fully grown crop of radishes or onions; that is when the two crops are grown in the same area. When determining the influence of the crop type on the daily crop water needs, reference is always made to a fully grown crop. Crops are said to be fully grown when the plants have reached their maximum height, when they optimally cover the ground, and when they possibly have started flowering or started grain setting. When the crops are fully-grown their water need is the highest. It is the so-called 'peak period' of their water needs.

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 a number of crops need more or less the same amount of water as grass. Table 8 indicates five groups of crops. The crops in column 1 need 30% less water than grass in their peak period. The crops in column 2 need 10% less water than grass. The crops in column 3 need the same amount of water as grass. The crops in columns 4 and 5 need respectively 10 and 20% more water than grass in their peak period.

Table 8. *Crop water needs in peak period of various field crops as compared to standard grass*

Column 1	Column 2	Column 3	Column 4	Column 5
–30%	–10%	Same as standard grass	+ 10%	+20%
Citrus	Cucumber	Carrots	Barley	Paddy rice
Olives	Radishes	Crucifers (cabbage, cauliflower, broccoli etc.)	Beans	Sugarcane
Grapes	Squash	Lettuce	Maize	Banana
		Melons	Flax	Nuts and fruit trees with cover crop
		Onions	Small grains	
		Peanuts	Cotton	
		Peppers	Tomato	
		Spinach	Egg plant	
		Tea	Lentils	
		Grass	Millet	
		Cacao	Oats	
		Coffee	Peas	
		Clean cultivated nuts and fruit trees, e.g. apples	Potatoes	
			Safflower	
			Sorghum	
			Soybeans	
			Sugar beet	
			Sunflower	
			Tobacco	
			Wheat	

EXAMPLE

A standard grass in a certain area needs 5 mm of water per day. It was found out in that same area, potatoes will need 10% more water. Therefore, 10% of 5 mm equals 0.5 mm. Thus potatoes would need 5 + 0.5 = 5.5 mm of water per day.

2.2.2 Influence of crop type on the seasonal crop water needs

The crop type not only has an influence on the **daily water need** of a fully grown crop, the peak daily water need, but also on the duration of the total growing season of the crop, and thus on the **seasonal water need** (Salter and Goode 1967). 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 the seed supplier, the Extension Service, the Irrigation Department or Ministry of Agriculture. The duration of the total growing season has an enormous influence on the seasonal crop water need. There are, for example, many rice varieties, some with a short growing cycle (e.g. 90 days) and others with a long growing cycle (e.g. 150 days). This has a strong influence on the seasonal rice water needs: a rice crop which is in the field for 150 days will need in total much more water than a rice crop which is only in the field for 90 days. For the two rice crops the **daily** peak water need may still be the same, but the 150 days crop will need this daily amount for a longer period.

The time of the year during which crops are grown is also very important. A certain crop variety grown during the cooler months will need substantially less water than the same crop variety grown during the hotter months.

Table 9 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 these values are only rough approximations and it is much better to obtain the values locally. As can be seen from Table 9 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.

Table 9. *Indicative values of the total growing period*

Crop	Total growing period (days)	Crop	Total growing period (days)
Alfalfa	100–365	Millet	105–140
Banana	300–365	Onion green	70–95
Barley/oats/wheat	120–150	Onion dry	150–210
Bean green	75–90	Peanut/Groundnut	130–140
Bean dry	95–110	Pea	90–100
Cabbage	120–140	Pepper	120–210
Carrot	100–150	Potato	105–145
Citrus	240–365	Radish	35–45
Cotton	180–195	Rice	90–150
Cucumber	105–130	Sorghum	120–130
Eggplant	130–140	Soybean	135–150
Flax	150–220	Spinach	60–100
Grain/small	150–165	Squash	95–120
Lentil	150–170	Sugar beet	160–230
Lettuce	75–140	Sugarcane	270–365
Maize sweet	80–110	Sunflower	125–130
Maize grain	125–180	Tobacco	130–160
Melon	120–160	Tomato	135–180

2.2.3 Influence of the growth stage of a crop on crop water needs

A fully-grown maize crop will need more water than a maize crop, which has just been planted. As discussed before, the crop water need or crop evapotranspiration consists of transpiration by the plant and evaporation from the soil and plant surface. When the plants are very small the evaporation will be more important than the transpiration. When the plants are fully-grown the transpiration is more important than the evaporation. Figure 13 shows, in a schematic way, the various development or growth stages of a crop (Salter and Goode 1967; FAO 1985).

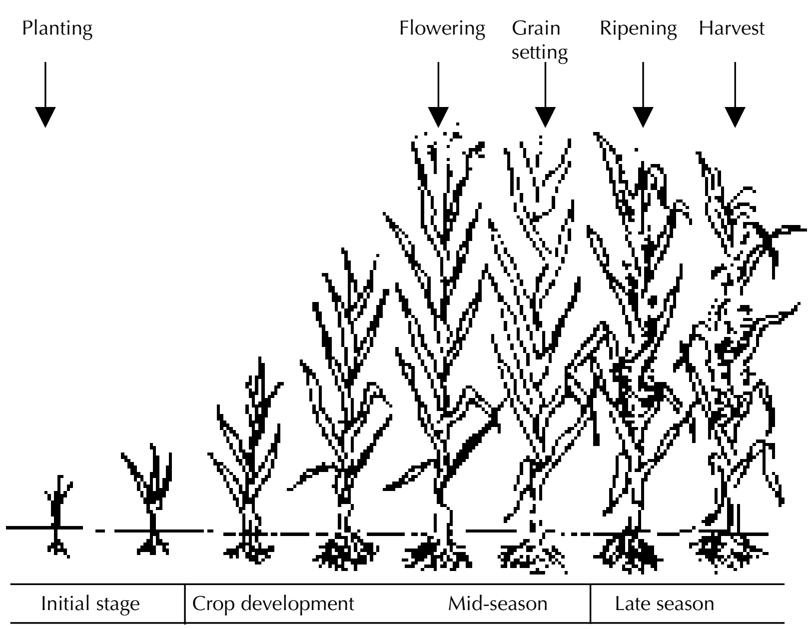


Figure 13. *Growth stages of a crop.*

At planting and during the initial stage, the evaporation is more important than the transpiration. The evapotranspiration or crop water needed during the initial stage is estimated at 50% of the crop water needed during the mid-season stage, when the crop is fully developed. During the so-called crop development stage the crop water need gradually increases from 50% of the maximum crop water need to the maximum crop water need. The maximum crop water need is reached at the end of the crop development stage, which is the beginning of the mid-season stage. With respect to the late season stage, which is the period during which the crop ripens and is harvested, a distinction can be made between two groups of crops:

Fresh harvested crops: such as lettuce, cabbage etc. With these crops the crop water need remains the same during the late season stage as it was during the mid-season stage. The crops are harvested fresh and thus need water up to the last moment.

Dry harvested crops: such as cotton, cereals, sunflower etc. During the late season stage these crops are allowed to dry out and sometimes even die. Thus their water needs during the late season stage are minimal. If the crop is indeed allowed to die, the water needs are only some 25% of the crop water need during the mid-season or peak period. No irrigation is given to these crops during the late season stage.

2.3 Determination of crop water needs

In the previous sections it was explained which factors—the climate, the crop type and the growth stage—the crop water need depends on. To calculate the water needs for the various months during which the crop is grown is fairly complicated. As stated before, it is often possible to obtain data on crop water needs locally and it is thus not necessary to calculate them. However, to give the reader some idea on values of seasonal water needs for the most important field crops, Table 10 can be used as a guide.

Table 10. *Approximate range values of seasonal crop water needs*

Crop	Crop water need (mm/total growing period)
Alfalfa	800–1600
Banana	1200–2200
Barley/oats/wheat	450–650
Bean	300–500
Cabbage	350–500
Citrus	900–1200
Cotton	700–1300
Maize	500–800
Melon	400–600
Onion	350–550
Peanut	500–700
Pea	350–500
Pepper	600–900
Potato	500–700
Rice (paddy)	450–700
Sorghum/millet	450–650
Soybean	450–700
Sugarbeet	550–750
Sugarcane	1500–2500
Sunflower	600–1000
Tomato	400–800

2.4 Effective rainfall

The plants cannot use all of the rainwater that falls on the soil surface. Part of the rainwater percolates below the root zone of the plants and part of the rainwater flows away over the soil surface as run-off (Figure 14). The plants cannot use deep percolated water and run-off water. In other words, part of the rainfall is not effective. The remaining part is stored in the root zone and can be used by the plants. This remaining part is the so-called effective rainfall. The factors, which influence how much rainfall is effective and not effective, include the climate, the soil properties and the depth of the root zone.

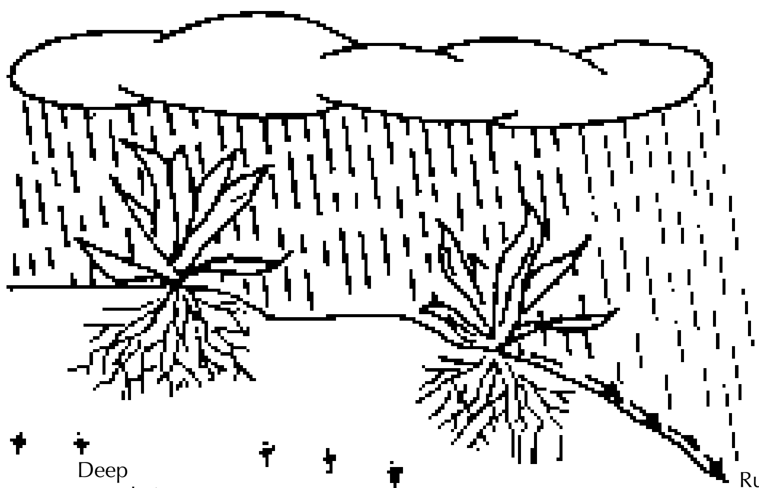


Figure 14. *Part of the rainwater is lost through deep percolation and run-off.*

If the rainfall is high, a relatively large part of the water is lost through deep percolation and run-off. Another factor, which needs to be taken into account when estimating the effective rainfall, is the variation of the rainfall over the years. Especially in low rainfall climates, the rain that does fall is often unreliable; one year may be relatively dry and another year may be relatively wet.

In many countries, formulae have been developed locally to determine the effective precipitation. Such formulae take into account factors like rainfall reliability, topography, prevailing soil type etc. If such formulae or other local data are available, they should be used. If such data are not available, Table 11 could be used to obtain a rough estimate of the effective rainfall.

Table 11. *Rainfall or precipitation (P) and effective rainfall or effective precipitation (Pe) in mm/month*

P (mm/month)	Pe (mm/month)	P (mm/month)	Pe (mm/month)
0	0	130	79
10	0	140	87
20	2	150	95
30	8	160	103
40	14	170	111
50	20	180	119
60	26	190	127
70	32	200	135
80	39	210	143
90	47	220	151
100	55	230	159
110	63	240	167
120	71	250	175

EXAMPLE

Estimate the effective rainfall in mm/month if the rainfall is 80 mm/month. From Table 11 it can be seen that the effective rainfall is 39 mm/month. This means that out of 80 mm/month, the plants can use 39 mm and it is estimated that the remaining 41 mm (80–39) is lost through deep percolation and run-off.

2.5 Irrigation water needs

The irrigation water need of a certain crop is the difference between the crop water need and the part of the rainfall that can be used by the crop (the effective rainfall). For each of the crops grown on an irrigation scheme, the crop water need is usually determined on a monthly basis. The crop water need is expressed in mm water layer per time unit, in this case mm/month. The effective rainfall is estimated on a monthly basis, using measured rainfall data, Table 11 or local information, if available (USDA 1962; Doorenbos and Pruitt 1977; FAO 1977; Taffa 2002; Panda 2005). For all crops and for each month of the growing season, the irrigation water need is calculated by subtracting the effective rainfall from the crop water need.

Irrigation water need = Crop water need – Effective precipitation

Chapter 3 Irrigation scheduling

Chapter objectives

After reading this chapter, you will be able to:

- describe the influence of water shortage on yields
- determine which crop is more sensitive to water shortage
- determine irrigation schedules by plant observation, estimation and simple calculation methods
- adjust irrigation schedule for estimation method
- determine duration of irrigation application

3.1 When and how much to irrigate

The irrigation schedule indicates **how much** irrigation water has to be given to the crop, and **how often or when** this water is given. How much and how often water has to be given depends on the **irrigation water need** of the crop (Hansen et al. 1980; Garg 1989; Taffa 2002; Panda 2005). The irrigation water need is defined as the crop water need minus the effective rainfall. It is usually expressed in mm/day or mm/month. When, for example, the irrigation water need of a certain crop, grown in a hot, dry climate is 8 mm/day (Figure15), this means that each day the crop needs a water layer of 8 mm over the whole area on which the crop is grown. This water has to be supplied by means of irrigation.

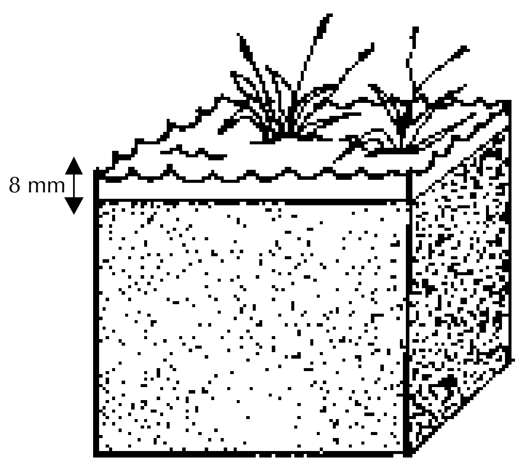
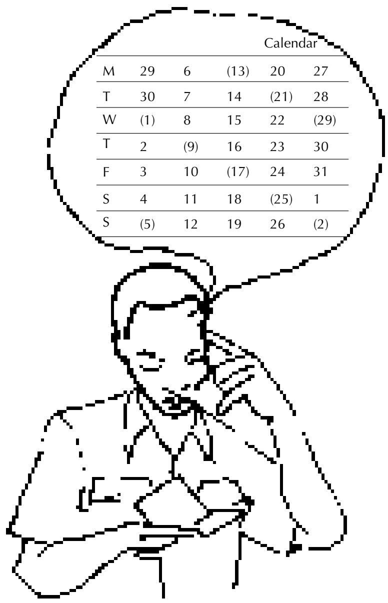


Figure 15. *Irrigation water need of 8 mm/day.*

An irrigation water need of 8 mm/day, however, does **not** mean that this 8 mm has to be supplied by irrigation **every day.** In theory, water could be given daily. But, this would be time and labour consuming. It is therefore preferable to have a longer irrigation interval (Figure 16). It is, for example, possible to supply 24 mm every 3 days or 40 mm every 5 days. The irrigation water will then be stored in the root zone and gradually be used by the plants say, 8 mm every day. The irrigation interval has to be chosen in such a way that the crop will not suffer from water shortage.

Bear in mind these questions and answers.

- How often to irrigate? Irrigate often enough to prevent the plants suffering from drought.
- How much to irrigate? Irrigate as much as the plants have used the water since the previous irrigation.



Source: FAO (1985).
Figure 16. *When to irrigate?*

If it is assumed that the soil is wet (e.g. at field capacity) on day 1 (Figure 17), the crop will have no difficulty in taking up the water for the first couple of days. When, however, more and more days pass—and no irrigation is given—the crop will have more and more difficulty in taking up the water.

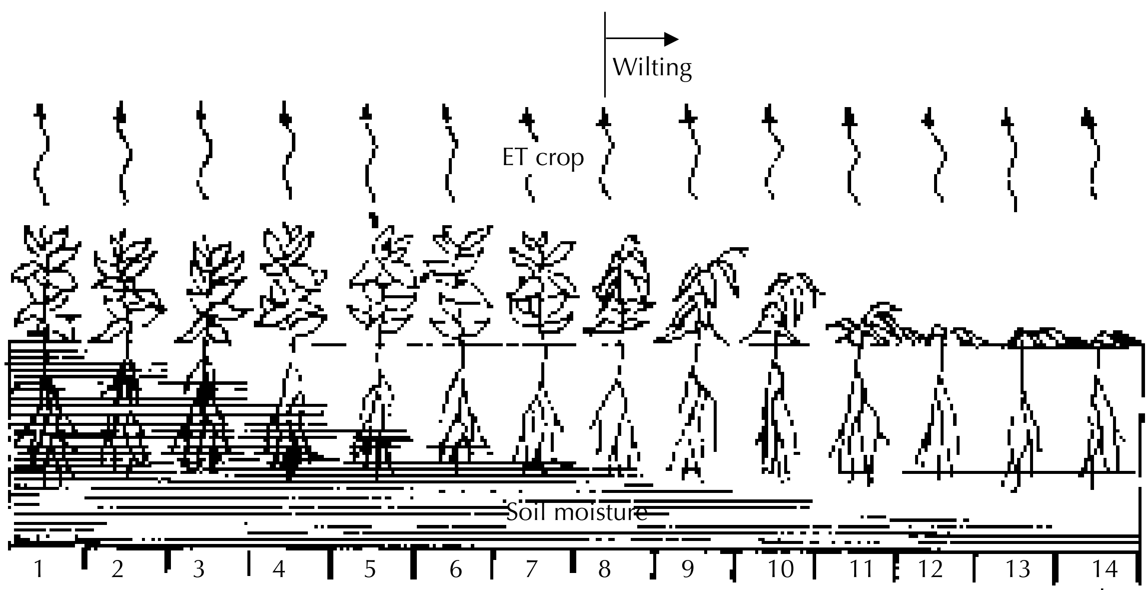


Figure 17. *In the absence of rainfall and irrigation water, the plants eventually die.*

In Figure 18 it can be seen that, in this soil, the plants start to suffer after approximately one week. Irrigation water should be given before this happens, in order to allow for optimal production. When, for example (Figure 19), irrigation water is given on day 5, on day 9, on day 13 etc., the plants will not suffer from water shortage.

In principle, the amount of irrigation water given in one irrigation application (irrigation depth) is the amount of water used by the plants since the previous irrigation. However, the amount of irrigation water which can be given during one irrigation application is limited**.** The **maximum amount**, which can be given, has to be determined and may be influenced by the soil type, root depth and the irrigation method.

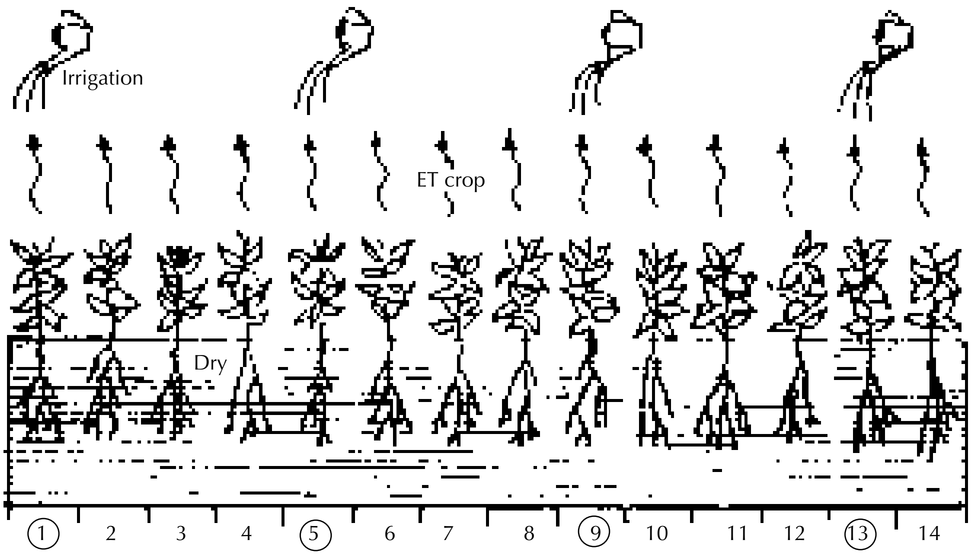


Figure 18. *If irrigation water is applied regularly, the plants do not suffer from water shortage.*

The **soil type** influences the maximum amount of water, which can be stored in the soil per meter depth. Sand can store only a little water or, in other words, sand has low available water content. On sandy soils it will be necessary to irrigate frequently with a small amount of water. Clay has high available water content. Therefore larger amounts of irrigation water can be applied to clayey soils, less frequently.

The **root depth** of a crop also influences the maximum amount of water, which can be stored in the root zone (Figure 19). If the root system of a crop is shallow, little water can be stored in the root zone and frequent—but small—irrigation applications are needed. With deep rooting crops more water can be taken up and more water can be applied, less frequently. Young plants have shallow roots compared to fully-grown plants. Thus, just after planting or sowing, the crop needs smaller and more frequent water applications than when it is fully developed.

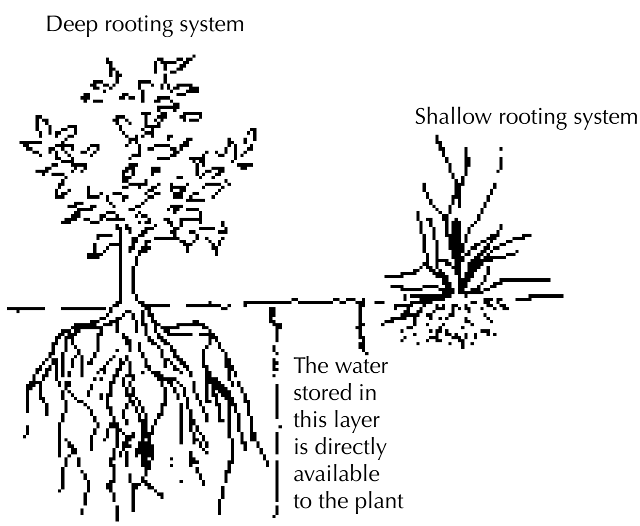


Figure 19. *Plants with deep roots take up water over a greater depth than shallow rooting plants.*

How much water can be infiltrated into the soil with the locally used **irrigation method** has to be checked in the field. For instance, when using basin irrigation, more water can be infiltrated during one irrigation application than when using furrow irrigation. With small-scale irrigation (small water flows and small fields) it is often the irrigation method, which is the limiting factor when determining the maximum irrigation application.

3.2 Influence of water shortages on yields

Ideally, in irrigation schemes, crops do not suffer from water shortages as irrigation water is applied before the crops are under drought stress. However, it may not be possible to apply the irrigation water exactly when it would be best; for example, in a dry year when the river may not have enough water to irrigate all the fields on time. The farmers may be badly organized and lose too much water at the upstream end of the scheme, thus causing problems downstream. The scheme management may decide to spread the available water over a large area, thus allowing more farmers to irrigate, although less than the optimal amount.

In such cases of unexpected or sometimes even planned water shortages, it is good to know:

(a) the crops which suffer most from water shortages, i.e. crops that will have severe yield reductions when the water is in short supply; and
(b) the growth stages during which the various crops suffer most from water shortages.

The economic value of the crops may also influence the decision on how best to divide scarce water.

3.2.1 Crops sensitive to water shortages

In general, crops grown for their fresh leaves or fruits are more sensitive to water shortages than those grown for their dry seeds or fruits. Table 12 shows four categories of crops; the categories are based on the sensitivity of the specific crops to drought. Crops like paddy rice, banana, potato and sugarcane are very sensitive to water shortage. This means that if they suffer even small water shortages, their yields will be reduced considerably. Such water shortages must be avoided. Crops like millet and sorghum, on the other hand, are only slightly sensitive to drought; they are drought resistant. If the water shortage does not last too long, the effect on the yield will be minimal. If various crops are grown on an irrigation scheme, (e.g. if sunflower and sugarcane are grown where water is in short supply), it is advisable to give priority to irrigating the most drought sensitive crop; in this case sugarcane.

Table 12. *Sensitivity of various field crops to water shortages*

Sensitivity	Low	Low–medium	Medium–high	High
Crops	Cassava	Alfalfa	Beans	Banana
	Cotton	Citrus	Cabbage	Fresh green vegetables
	Millet	Grape	Maize	Paddy rice
	Pigeon pea	Groundnuts	Onion	Potato
	Sorghum	Soybean	Peas	Sugarcane
		Sugar beet	Pepper	
		Sunflower	Tomato	
		Wheat	(Water) melon	

3.2.2 Growth stages sensitive to water shortages

The total growing season of an annual crop can be divided into four growth stages:

1. initial stage; from sowing to 10% ground cover
2. crop development stage; from 10 to 70% ground cover
3. mid-season stage; including flowering and grain setting or yield formation
4. late season stage; including ripening and harvest.

In general it can be stated that of the four growth stages, the **mid-season stage is most sensitive to water shortages.** This is mainly because it is the period of the highest crop water needs. If water shortages occur during the mid-season stage, the negative effect on the yield will be pronounced. The least sensitive to water shortages is the late season stage. This stage includes ripening and harvest. Water shortages in this stage have—especially if the crop is harvested dry—only a slight effect on the yield. However, care should be taken during this stage with crops, which are harvested fresh, such as lettuce. Fresh harvested crops are also sensitive to water shortages during the late season stage. Table 13 indicates the growth stages most sensitive to water shortages for various important field crops. On an irrigation project, if only one crop is grown, but not all fields have been planted at the same time (staggered planting), and water is in short supply, it is advisable to give priority to irrigating those fields on which the crop has reached the mid-season stage (flowering and yield formation).

Table 13. *Periods sensitive to water shortages*

Crop	Sensitive period
Alfalfa	Just before cutting
Alfalfa (for seed production)	Flowering
Banana	Throughout
Bean	Flowering and pod filling
Cabbage	Head enlargement and ripening
Citrus	Flowering and fruit setting more than fruit enlargement
Cotton	Flowering and boll formation
Grape	Vegetative period and flowering more than fruit filling
Groundnut	Flowering and pod setting
Maize	Flowering and grain filling
Olive	Just prior to flowering and yield formation
Onion	Bulb enlargement
Onion (for seed production)	Flowering
Pea/fresh	Flowering and yield formation
Pea/dry	Ripening
Pepper	Throughout
Pineapple	Vegetative period
Potato	Tuber initiation
Rice	Head development and flowering
Sorghum	Flowering and yield formation
Soybean	Flowering and yield formation
Sugar beet	First month after emergence
Sugarcane	Vegetative period (stem elongation)
Sunflower	Flowering
Tobacco	Period of rapid growth
Tomato	Flowering
Watermelon	Flowering and fruit filling
Wheat	Flowering

3.3 Determining irrigation schedule for crops other than rice

The accurate determination of an irrigation schedule is a time-consuming and complicated process. In modern 'high tech' farming systems, the introduction of computer programs has made it easier and it is possible to schedule the irrigation water supply exactly according to the water needs of the crops. Ideally, at the beginning of the growing season, the amount of water given per irrigation application, also called the irrigation depth, is small and given frequently. This is due to the low evapotranspiration of the young plants and their shallow root depth. During the mid season, the irrigation depth should be larger and given less frequently due to high evapotranspiration and maximum root depth. Thus, the irrigation depth and/or the irrigation interval (or frequency) vary with the crop development.

When sprinkler and drip irrigation methods are used, it may be possible and practical to vary both the irrigation depth and interval during the growing season. With these methods it is just a matter of turning on the tap for longer/shorter time periods or less/more frequently. When surface irrigation methods are used, however, it is not very practical to vary the irrigation depth and frequency too much. With surface irrigation, variations in irrigation depth are only possible within limits. It is also very confusing for the farmers to change the schedule all the time. Therefore, it is often sufficient to estimate or roughly calculate the irrigation schedule and to fix the most suitable depth and interval. In this chapter, three simple methods to determine the irrigation schedule are briefly described: plant observation method, estimation method and simple calculation method. Soil moisture measurement method can also be employed if appropriate instruments are available.

The **plant observation method** is the method, which is normally used by farmers in the field, to estimate 'when' to irrigate. The method is based on observing changes in plant characteristics, such as changes in colour of the plants, curling of the leaves and ultimately plant wilting. In the **estimation method**, a table is provided with irrigation schedules for the major field crops grown under various climatic conditions. The **simple calculation method** is based on the estimated depth (in mm) of the irrigation application, and the calculated irrigation water need of the crop during the growing season.

3.3.1 Plant observation method

The plant observation method determines when the plants have to be irrigated and is based on observing changes in the plant characteristics, such as changes in colour of the plants, curling of the leaves and plant wilting. The changes can often be detected by looking at the crop as a whole rather than at the individual plants. When crops come under water stress, their appearance changes from vigorous growth (green leaves) to slow or no growth (when fewer young leaves are darker in colour). Many crops react to water stress by changing their leaf orientation. With adequate water available, the leaves are perpendicular to the sun (thus allowing optimal transpiration and production). However, when little water is available, the leaves turn away from the sun (thus reducing the transpiration and production).

To use the plant observation method successfully, experience is required as well as a good knowledge of the local circumstances. The disadvantage of the plant observation method is that by the time the symptoms are evident, the irrigation water has already been withheld too long for most crops and yield losses are already inevitable.

3.3.2 Estimation method

3.3.2.1 Estimating the irrigation schedule

In this section, a table is provided to estimate the irrigation schedule for the major field crops during the period of peak water demand while the schedules are given for three different soil types and three different climates. The table is based on calculated crop water needs and an estimated root depth for each of the crops under consideration. The table assumes that with the irrigation method used the maximum possible net application depth is 70 mm. With respect to soil types**,** a distinction has been made between sand, loam, and clay, which have low, medium and high available water content, respectively. With respect to **climate,** a distinction is made between three different climates (FAO 1985).

Table 14. *Variation of ETo based on soil and climate types*

Shallow and/or sandy soil	In a sandy soil or a shallow soil (with a hard pan or impermeable layer close to the soil surface), little water can be stored; irrigation will thus have to take place frequently but little water is given per application
Loamy soil	In a loamy soil more water can be stored than in a sandy or shallow soil. Irrigation water is applied less frequently and more water is given per application
Clayey soil	In a clayey soil even more water can be stored than in a medium soil. Irrigation water is applied even less frequently and again more water is given per application
Climate 1	Represents a situation where the reference crop evapotranspiration ETo = 4–5 mm/day
Climate 2	Represents an ETo = 6–7 mm/day
Climate 3	Represents an ETo = 8–9 mm/day

An overview indicating in which climatic zones these ETo values can be found is given below:

Table 15. *Reference crop evapotranspiration (mm/day)*

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

It is important to note that the irrigation schedules given in Table 16 are based on the crop water needs in the **peak period.** It is further assumed that **little or no rainfall occurs** during the growing season.

Some examples on the use of Table 16 are given below.

EXAMPLES

1. Estimate the irrigation schedule for groundnuts grown on a deep, clayey soil, in a hot and dry climate. Firstly, the climatic class has to be identified: climate 3 (ETo = 8–9 mm/day) represents a hot climate. Table 16 shows that for climate 3 the interval for groundnuts grown on a clayey soil is 6 days and the net irrigation depth is 50 mm. This means that every 6 days the groundnuts should receive a net irrigation application of 50 mm.
2. Estimate the irrigation schedule for spinach grown on a loamy soil, in an area with an average temperature of 12ºC during the growing season. The average temperature is low: climate 1 (ETo = 4–5 mm/day). Table 16 shows, with climate 1, for spinach, grown on a loamy soil an interval of 4 days and a net irrigation depth of 20 mm.
3. Estimate the irrigation schedule of sorghum grown on a sandy soil, in an area with a temperature range of 15–25ºC during the growing season.

The average temperature is medium: climate 2 (ETo = 6–7 mm/day). Table 16 shows, with climate 2 for sorghum grown on a sandy soil, an irrigation interval of 6 days and a net irrigation depth of 40 mm.

Table 16. *Estimated irrigation schedules for major field crops during peak water use*

Climate	Shallow and/or sandy soil				Loamy soil				Clayey soil			
	Interval (days)			Net irr. depth (mm)	Interval (days)			Net irr. depth (mm)	Interval (days)			Net irr. depth (mm)
	1	2	3		1	2	3		1	2	3	
Alfalfa	9	6	5	40	13	9	7	60	16	11	8	70
Banana	5	3	2	25	7	5	4	40	10	7	5	55
Barley/oats	8	6	4	40	11	8	6	55	14	10	7	70
Beans	6	4	3	30	8	6	4	40	10	7	5	50
Cacao	9	6	5	40	13	9	7	60	16	11	8	70
Carrot	6	4	3	25	7	5	4	35	11	8	6	50
Citrus	8	6	4	30	11	8	6	40	15	10	8	55
Coffee	9	6	5	40	13	9	7	60	16	11	8	70
Cotton	8	6	4	40	11	8	6	55	14	10	7	70
Cucumber	10	7	5	40	15	10	8	60	17	12	9	70
Crucifers*	3	2	2	15	4	3	2	20	7	5	4	30
Eggplant	6	4	3	30	8	6	4	40	10	7	5	50
Flax	8	6	4	40	11	8	6	55	14	10	7	70
Fruit trees	9	6	5	40	13	9	7	60	16	11	8	70
Grains, small	8	6	4	40	11	8	6	55	14	10	7	70
Grapes	11	8	6	40	15	11	8	55	19	13	10	70
Grass	9	6	5	40	13	9	7	60	16	11	8	70
Groundnuts	6	4	3	25	7	5	4	35	11	8	6	50
Lentils	6	4	3	30	8	6	4	40	10	7	5	50
Lettuce	3	2	2	15	4	3	2	20	7	5	4	30
Maize	8	6	4	40	11	8	6	55	14	10	7	70
Melons	9	6	5	40	13	9	7	60	16	11	8	70
Millet	8	6	4	40	11	8	6	55	14	10	7	70
Olives	11	8	6	40	15	11	8	55	19	13	10	70
Onions	3	2	2	15	4	3	2	20	7	5	4	30
Peas	6	4	3	30	8	6	4	40	10	7	5	50
Peppers	6	4	3	25	7	5	4	35	11	8	6	50
Potatoes	6	4	3	30	8	6	4	40	10	7	5	50
Radish	4	3	2	15	5	4	3	20	7	5	4	30
Safflower	8	6	4	40	11	8	6	55	14	10	7	70
Sorghum	8	6	4	40	11	8	6	55	14	10	7	70
Soybeans	8	6	4	40	11	8	6	55	14	10	7	70
Spinach	3	2	2	15	4	3	2	20	7	5	4	30
Squash	10	7	5	40	15	10	8	60	17	12	9	70
Sugarbeet	8	6	4	40	11	8	6	55	14	10	7	70
Sugarcane	7	5	4	40	10	7	5	55	13	9	7	70
Sunflower	8	6	4	40	11	8	6	55	14	10	7	70
Tea	9	6	5	40	13	9	7	60	16	11	8	70
Tobacco	6	4	3	30	8	6	4	40	10	7	5	50
Tomatoes	6	4	3	30	8	6	4	40	10	7	5	50
Wheat	8	6	4	40	11	8	6	55	14	10	7	70

*Cabbage, cauliflower etc.

3.3.2.2 Adjusting the irrigation schedule

a. Adjustments for the non-peak periods

The irrigation schedule, which is obtained using Table 16, is valid for the peak period; in other words, for the mid-season stage of the crop. During the **early growth stages,** when the plants are small, the crop water need is less than during the mid-season stage. Therefore, it may be possible to irrigate with the same frequency as during the mid-season, during the early stages of crop growth, but with smaller irrigation applications. It is risky to give the same irrigation application as during the mid-season, but less frequently; the young plants may suffer from water shortage, as their roots are not able to take up water from the lower layers of the root zone. Dry harvested crops or crops which are allowed to die before harvest (for example grain maize), need less water during the **late season stage** than during the mid-season stage (the peak period). During the late season stage, the roots of the crops are fully developed and therefore the same amount of water can be stored in the root zone as during the mid-season stage. It is thus possible to irrigate during the late season stage less frequently but with the same irrigation depth as during the peak period.

b. Adjustment for climates with considerable rainfall during the growing season

The schedules obtained from Table 16 are based on the assumption that little or no rainfall occurs during the growing season. If the contribution from the rainfall is considerable during the growing season, the schedules need to be adjusted: usually by making the interval longer. It may also be possible to reduce the net irrigation depth. It is difficult to estimate to which values the interval and the irrigation depth should be adjusted. It is therefore suggested to use the simple calculation method instead of the estimation method, in the case of significant rainfall during the growing season. Alternatively it is possible to adjust the irrigation schedule to the actual rainfall.

c. Adjustment for local irrigation practices or irrigation method used

The net irrigation depth obtained from Table 16 may not be suitable for the local conditions. It may not be possible, for example, to infiltrate 70 mm with the irrigation method used locally. Tests may have shown that it is only possible to infiltrate some 50 mm per application. In such cases, both the net irrigation depth and the interval must be adjusted simultaneously. For example, suppose that maize is grown on a clayey soil in a moderately warm climate. According to Table 16, the interval is 10 days and the net irrigation depth is 70 mm. This corresponds to an irrigation water need of 70/10 = 7 mm/day.

Instead of giving 70 mm every 10 days, it is also possible to give: 63 mm every 9 days; 56 mm every 8 days; 49 mm every 7 days; 42 mm every 6 days etc. This means that in the above example an interval of seven days is chosen with a net application depth of 49 mm.

d. Adjustment for shallow soils

A soil, which is shallow, can only store a small amount of water, even if the soil is clayey. For shallow soils—sandy, loamy or clayey—the column 'shallow and/or sandy soil' of Table 14 should be used.

e. Adjustment for salt-affected soils

In the case of irrigating salt-affected soils, special attention needs to be given to the determination of the irrigation schedule.

3.3.3 Simple calculation method

The simple calculation method to determine the irrigation schedule is based on the estimated depth (in mm) of the irrigation applications and the calculated irrigation water need of the crop over the growing season. Unlike the estimation method, the simple calculation method is based on calculated irrigation water needs. Thus, the influence of the climate, i.e. temperature and rainfall, is more accurately taken into account. The result of the simple calculation method will therefore be more accurate than the result of the estimation method. The simple calculation method to determine the irrigation schedule involves the following steps:

Step 1: Estimate the net and gross irrigation depth (d) in mm

The net irrigation depth is the amount of irrigation water required to bring the soil moisture level in the effective root zone to field capacity. The net irrigation depth is best determined locally by checking how much water is given per irrigation application with the local irrigation method and practice. If no local data is easily available, Table 17 can be used to estimate the net irrigation depth (d_{net}), in mm. As can be seen from the table, the net irrigation depth is assumed to depend only on the root depth of the crop and on the soil type. It must be noted that the d_{net} values in the table are approximate values only. Also the root depth is best determined locally. If no data are available, Table 18 can be used which gives an indication of the root depth of the major field crops.

Table 17. *Approximate net irrigation depths, in mm*

	Shallow rooting crops	Medium rooting crops	Deep rooting crops
Shallow and/or sandy soil	15	30	40
Loamy soil	20	40	60
Clayey soil	30	50	70

Table 18. *Approximate root depth of the major field crops*

Shallow rooting crops (30–60 cm):	Crucifers (cabbage, cauliflower etc.), celery, lettuce, onions, pineapple, potatoes, spinach, other vegetables except beets, carrots, cucumber
Medium rooting crops (50–100 cm):	Bananas, beans, beets, carrots, clover, cacao, cucumber, groundnuts, palm trees, peas, pepper, sisal, soybeans, sugar beet, sunflower, tobacco, tomatoes
Deep rooting crops (90–150 cm):	Alfalfa, barley, citrus, cotton, dates, deciduous orchards, flax, grapes, maize, melons, oats, olives, safflower, sorghum, sugarcane, sweet potatoes, wheat

The plants cannot use all of the water applied to a field. Part of the water is lost through deep percolation and runoff. To reflect this water loss, the field application efficiency (ea) is used. The total amount of water applied through irrigation is termed as gross irrigation. In other words, it is net irrigation requirement plus losses in water application and other losses. The gross irrigation depth (d_{gross}), in mm, takes into account the water loss during the irrigation application and is determined using the following formula:

$$d_{gross} = \frac{100 \times d_{net}}{ea}$$

where, d_{gross} is gross irrigation depth in mm, d_{net} is net irrigation depth in mm, and ea is field application efficiency in percent. If reliable local data are available on the field application efficiency, these should be used. If such data are not available, the following values for the field application efficiency can be used:

Table 19. *Irrigation efficiencies*

For surface irrigation	ea = 60%
For sprinkler irrigation	ea = 75%
For drip irrigation	ea = 90%

If, for example, tomatoes are grown on a loamy soil, Tables 17 and 18 show that the estimated net irrigation depth is 40 mm. If furrow irrigation is used, the field application efficiency is 60% and the gross irrigation depth is determined as follows:

$$d_{gross} = \frac{100 \text{ x } d_{net}}{ea} = \frac{100 \text{ x} 40}{60} = 66.7 \approx 67 \text{ mm}$$

Step 2: Calculate the irrigation water need (IN) over the total growing season

This has been discussed in detail in the previous chapter. Assume that the irrigation water need (in mm/month) for tomatoes, planted 1 February and harvested 30 June, is as follows:

	Feb.	Mar.	Apr.	May	June
IN (mm/month)	67	110	166	195	180

The irrigation water need of tomatoes for the total growing season (February–June) is thus (67 + 110 + 166 + 195 + 180 =) 718 mm. This means that over the total growing season a net water layer of 718 mm has to be brought onto the field. If no data on irrigation water needs are available, the estimation method should be used.

Step 3: Calculate the number of irrigation applications over the total growing season

The number of irrigation applications over the total growing season can be obtained by dividing the irrigation water need over the growing season (Step 2) by the net irrigation depth per application (Step 1). If the net depth of each irrigation application is 40 mm (d_{net} = 40 mm; Step 1), and the irrigation water need over the growing season is 718 mm (Step 2), then a total of (718/40 =) 18 applications are required.

Step 4: Calculate the irrigation interval (INT) in days

Thus a total of 18 applications are required. The total growing season for tomatoes is 5 months (February–June) or 5 x 30 = 150 days. Eighteen applications in 150 days correspond to one application every 150/18 = 8.3 days.

In other words, the interval between two irrigation applications is 8 days. To be on the safe side, the interval is always rounded off to the lower whole figure: for example 7.6 days become 7 days; 3.2 days become 3 days.

3.3.4 Soil moisture measurement method

Another method used to determine the irrigation schedule involves soil moisture measurements in the field. When the soil moisture content has dropped to a certain critical level, irrigation water is applied. Instruments to measure the soil moisture include gypsum blocks, tensiometers and neutron probes. Their use, however, is beyond the scope of this manual.

3.4 Duration of irrigation application

Step 1: Estimate the net application depth and irrigation interval
Example for onion on loamy soil and ETo = 6 mm/day, climate 2.
Irrigation interval = 4 days and net irrigation depth is 24 mm.

Step 2: Gross irrigation depth
For surface irrigation method, irrigation efficiency is 60%
Gross irrigation depth is 24 mm /60% = 40 mm

Step 3: Measure plot size and water discharge at plot gate
In this example let's assume plot size is 0.25 ha and discharge at plot gate 5 litre/sec

Step 4 Calculate irrigation duration
Gross irrigation depth = 40 mm = 400 m^3/ha. Hence you need to give 100 m^3 to a 0.25 ha plot.
Plot at discharge = 5 litre/sec = 18 m^3/h   1 litre/sec = 3.6 m^3/h.
Irrigation duration is: 100 m^3/18 m^3/h = 5.56 h = 5 h 34′ rounded up to 5 h 40′.

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Module 4

Pumps for small-scale irrigation

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Introduction

Water can be conveyed by means of natural slopes, by lifting to a higher point and by means of pumps and pressurized pipelines. Devices for water lifting range from age-old indigenous water lifts to highly efficient pumps, which operate by electric, petrol or diesel motors (Garg 1989; Michael 1990). A pump is a device used to raise, transfer, or compress liquids and gases. There are four general classes of pumps, namely reciprocating, centrifugal, jet and other pumps. In each of the four classes, steps are taken to prevent cavitation (the formation of a vacuum), which would reduce the flow and damage the structure of the pump. Pumps used for gases and vapors are usually known as compressors.

The indigenous water lifts were manually operated or animal-operated (Michael 1990). Based on the optimum range in the height of lift, they can be grouped as low, medium and high head water lift. The engine-powered pumps are classified into two major groups as positive and variable displacement pumps. The **positive displacement pumps** are again subdivided into reciprocating and rotary pumps. The reciprocating pump can either be a lift or a force pump. Both lift and force pumps can either be single acting or double acting pumps. The **variable displacement pumps** are subdivided into centrifugal, mixed-flow, propeller, jet and air lift pumps. The centrifugal pumps are further subdivided into volute, diffuser and turbine pumps. The volute pumps can be a single stage or a multistage type. The turbine pumps can be grouped as deep well and submersible turbine pumps. This module deals with pumps that can be used for small-scale irrigation.

Reciprocating pumps consist of a piston moving back and forth in a cylinder that has valves to regulate the flow of liquid into and out of the cylinder. These pumps may be single or double acting. In the single acting pump, the pumping action takes place on only one side of the piston, as in the case of the common lift pump, in which the piston is moved up and down by hand. In the double acting pump, the pumping action takes place on both sides of the piston, as in the electrical or steam-driven boiler feed pump, in which water is supplied to a steam boiler under high pressure. These pumps can be single-stage or multistaged. Multistaged reciprocating pumps have multiple cylinders in series.

Centrifugal pumps, also known as rotary pumps, have a rotating impeller known as a blade that is immersed in the liquid. Liquid enters the pump near the axis of the impeller, and the rotating impeller sweeps the liquid out toward the ends of the impeller blades at high pressure. The impeller also gives the liquid a relatively high velocity that can be converted into pressure in a stationary part of the pump, known as the diffuser. In high-pressure pumps, a number of impellers may be used in series, and the diffusers following each impeller may contain guide vanes to gradually reduce the liquid velocity. For lower-pressure pumps, the diffuser is generally a spiral passage, known as a volute, with its cross-sectional area increasing gradually to reduce the velocity efficiently. The impeller must be primed before it can begin operation—that is, the impeller must be surrounded by liquid when the pump is started. Placing a checkvalve in the suction line, which holds the liquid in the pump when the impeller is not rotating, can do this. If this valve leaks, the pump may need to be primed by the introduction of liquid from an outside source such as the discharge reservoir. A centrifugal pump generally has a valve in the discharge line to control the flow and pressure.

Jet pumps use a relatively small stream of liquid or vapor, moving at high velocity, to move a larger flow of fluid. As the high-velocity stream passes through the fluid, it carries some of the fluid out of the pump; at the same time, the high-velocity stream creates a vacuum that pulls f uid into the pump. Jet pumps are often used to inject water into a steam boiler. Jet pumps have also been used to propel boats, particularly in shallow water where a conventional propeller might be damaged.

A variety of positive-displacement pumps are also available, generally consisting of a rotating member with a number of lobes that move in a close-fitting casing. The liquid is trapped in the spaces between the lobes and then discharged into a region of higher pressure. A common device of this type is the gear pump, which consists of a pair of meshing gears. The lobes in this case are the gear teeth.

Chapter 1 Basic concepts of energy and power

Chapter objectives:

Upon the completion of this chapter, you will be able to:

- define energy and power
- calculate energy and power

1.1 Energy measurement

Energy enables one to lift or pump water. Joule (J) is the international energy unit in the metric measurement system. Since a joule is a very small amount of energy,[1] engineers use Watt-hour (Wh) where 1 Wh = 3600 joules or kilowatt-hour (kWh) = 1000 Wh. An important aspect of energy is that it can be changed from one form to another. People and animals can convert food (= chemical energy) into mechanical energy to drive their muscles. In a typical pumping system powered by a petrol engine, the energy is changed three times before the water uses it. Chemical energy contained within the gasoline is burnt in the engine to produce mechanical energy. This is passed to the pump via a drive shaft and finally to the water via an impeller in the case of centrifugal pumps (Figure 1).

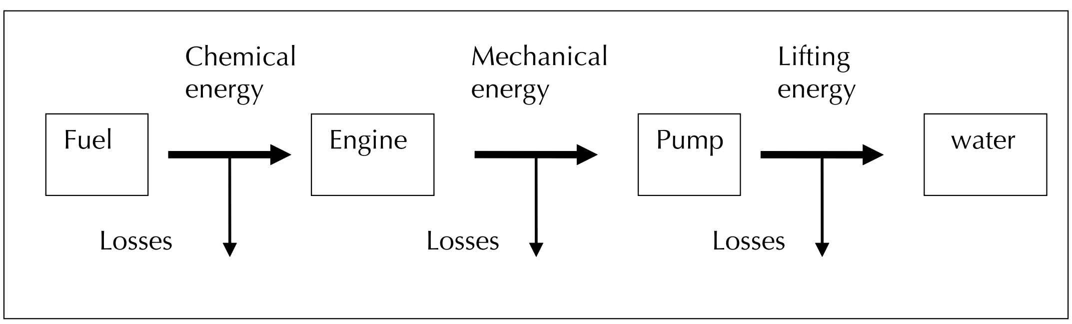


Figure 1. *Energy conversion and losses in a pumping system.*

The system of energy transfer is not perfect and energy losses occur through friction between the moving parts, water and pipes, and are usually lost as heat energy: An engine heats as fuel is burnt to provide power. Energy losses can be very high in pumping systems, and so can be costly in terms of fuel use.

1.2 Calculating energy

The amount of energy required to lift water depends on the volume of water to be lifted and the head (lifting height) required (equations 1a and b).

$$E = \frac{V_w H}{367} \quad (1a)$$

$$E = \frac{V_{wl} H}{367} \quad (1b)$$

where E is energy in kilowatt hour (kWh) or in Watt hour (Wh), V_w is volume of water in m^3, V_{wl} is volume of water in litres and H is the head in metres.

1. One joule enables to lift one litre of water of 10 centimetres.

Example 1.1

In a small irrigation scheme, irrigation water needs are 600 m³/day. Calculate the energy required each day for lifting water 10 metres above the water source as in Figure 2.

(Answer: 16.3 kWh)

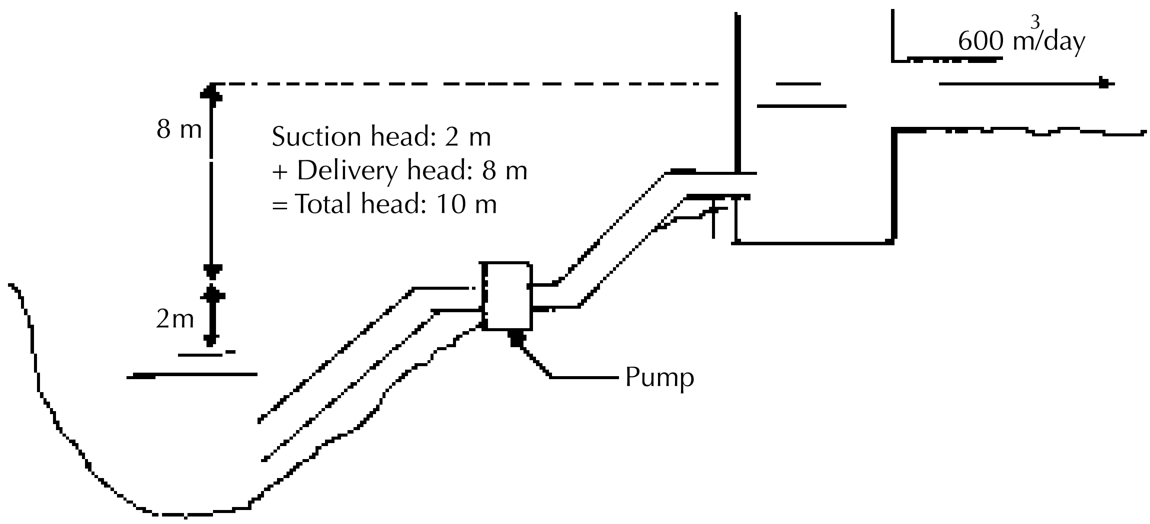


Figure 2. *Water lifting to a height of 10 m.*

1.3 Power

Power is often confused with energy. They are related but have different meanings. Energy is the capacity to lift water. **Power is the rate of using energy** and is commonly measured in watt (W) or kilowatt (kW), 1 kW = 1000 W. Another measure of power is horsepower (hp) (1 kW = 1.36 hp). Power is calculated as:

$$P = \frac{E}{t} \quad (2)$$

where P is power in Watt, E is energy in watt hour and t is time in hour. Discharge is volume of water f ow divided by the time elapsed. Using this relationship, Equation 3 is derived from Equations 1 and 2.

$$P = 9.81QH \quad (3)$$

where Q is discharge in litres per second (litres/sec).

Example 1.2

In example 1.1, it was calculated that the energy required each day to lift 600 m³ of water through 10 metres was 16.3 kWh. Calculate the power required in kW if

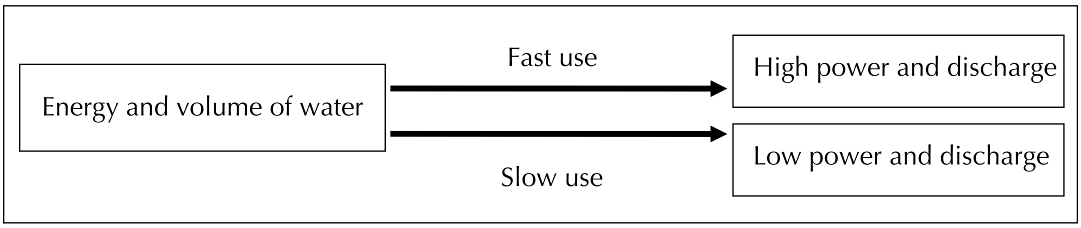
- Pumping is 12 hours/day
- Pumping is 8 hours/day
- Pumping is 4 hours 30′ per day

And in each case calculate the pump discharge in m^3/h and litre/sec.

Answers

	Power	Pump discharge	
Pumping 12 hours/day	1.36 kW	50 m3/h	14 litres/sec
Pumping 8 hours/day	2.04 kW	75 m3/h	31 litres/sec
Pumping 4 hours 30′/day	3.62 kW	133 m3/h	37 litres/sec

Reminder! Power is the rate of using energy.



Chapter 2 Selecting power source: Human power and engines

Chapter objectives:

Upon the completion of this chapter, you will be able to:

- understand the operation and irrigation capacity of treadle pumps
- understand centrifugal pumps
- explain the criteria for selecting irrigation pumps

There are many types of water pumps being used for irrigation and each pump type has different characteristics and capabilities (Michael 1990). A pumping unit or 'pump' has a source of power or engine to drive the pump that lifts water from the water source. The most common power sources in Ethiopia are human power, diesel and gasoline. Electric motors are more reliable and cheaper than petrol or diesel motors. As there is little rural electrification in Ethiopia they are seldom used. Developing micro hydropower units on streams of Ethiopian highlands is certainly an option worth considering.

Solar (still expensive) and wind-powered pumps (depending on wind conditions) are more appropriate for domestic or livestock water supply since they do not usually provide enough steady power to pump the volume of water required for irrigation. Animal powered pumps (noria, shadouf) have been in use for centuries in some parts of the world but not in Ethiopia. Furthermore animals have to be fed. Past experience in West Africa shows that this cost has been generally underestimated by people promoting animal-powered pumping.

2.1 Human power

The treadle pump (commonly known as pedal pump) is a water-lifting device similar in principle to the hand pump (Kay and Brabben 2000; Shigemichi and Shinohara 2004; Mangisoni 2006). The difference lies in the fact that a hand pump consists of a single barrel or cylinder and one has to pump up water with one's hands, whereas the pedal pump comprises two cylinders (Figure 3) and requires foot operation for lifting water (hence called a pedal pump). It is so simple to use that even a child, a woman or even an old person can operate the pump by manipulating his/her body weight on two foot pedals or treadles and by holding a bamboo or wooden frame for support. One can even make a comfortable sitting arrangement and pedal while being seated.

Most treadle pumps release water into furrows, as they have no delivery pressure. The '*Super Money Maker*' treadle pump manufactured by ApproTEC in Kenya has a delivery pressure of about 10 metres, and thus can release water through a f exible pipe on top of the crops. A reasonably fit man between 20 and 40 years old can produce a steady power output of 70 Watts (= 0.1 hp) (see Photo 1). However it is not possible to convert all the 70 Watts into useful water pumped because of losses through friction in the pump, valves and pipes. A useful water lifting power of 35 Watts is a reasonable estimation for a man operating a treadle pump. The discharge and head for a useful power of 35 Watts can be calculated (Equation 3) and are given in Table 1. Photos 2 and 3 show various treadle pumps.

Table 1. *Treadle pump discharge and head assuming a useful power output of 35 Watts.*

Head (m)	1.0	2.0	3.0	4.0
Discharge (litres/sec)	3.6	1.8	1.2	0.9

In practice, treadle pumps can be used when the required suction head does not exceed 4 to 6 metres.

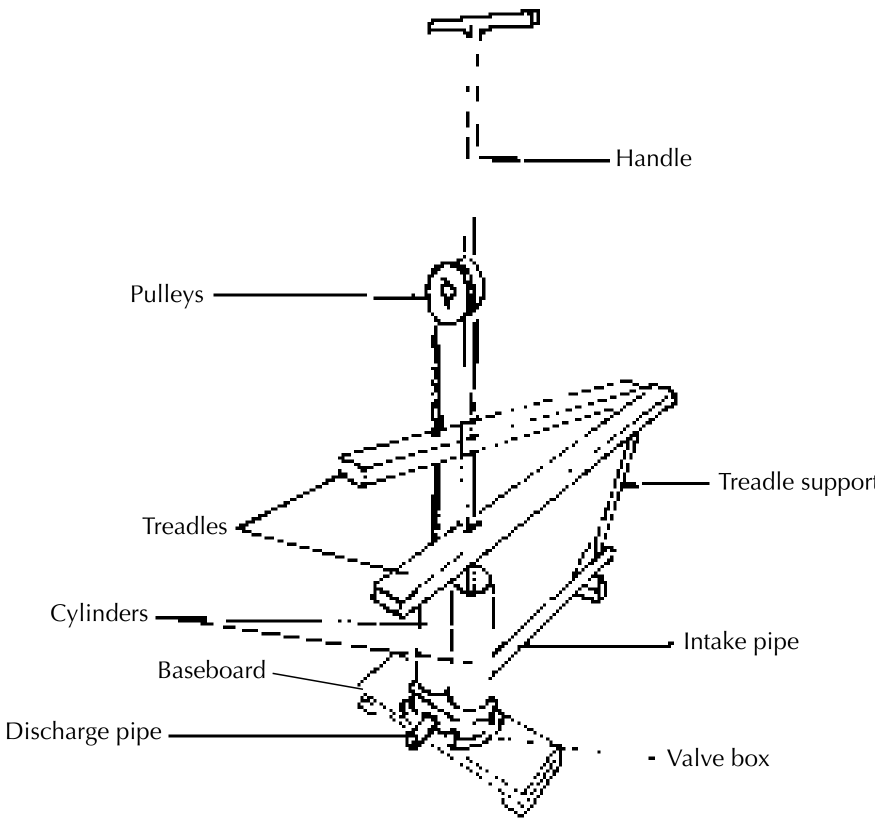


Figure 3. *Treadle pump.*

Photo 1. *Kickstart Money Maker Pump (Courtesy, Kickstart*).

Photo 2. *Treadle pumps (IWMI 2006).*

Malawi: Treadle pump models (from left)—Balaji metal treadles/pulley; MG Industries/pulley; Advaith, wooden treadles; Zim metal treadles/pulley; MG Industries/bicycle cog and chain; Pipeco, Mw wooden treadles/rubber pulley; Balaji metal treadles/pivot (Photo: Z Jere, Total Landcare Malawi and H Phombeya, Land Resource Centre Malawi).

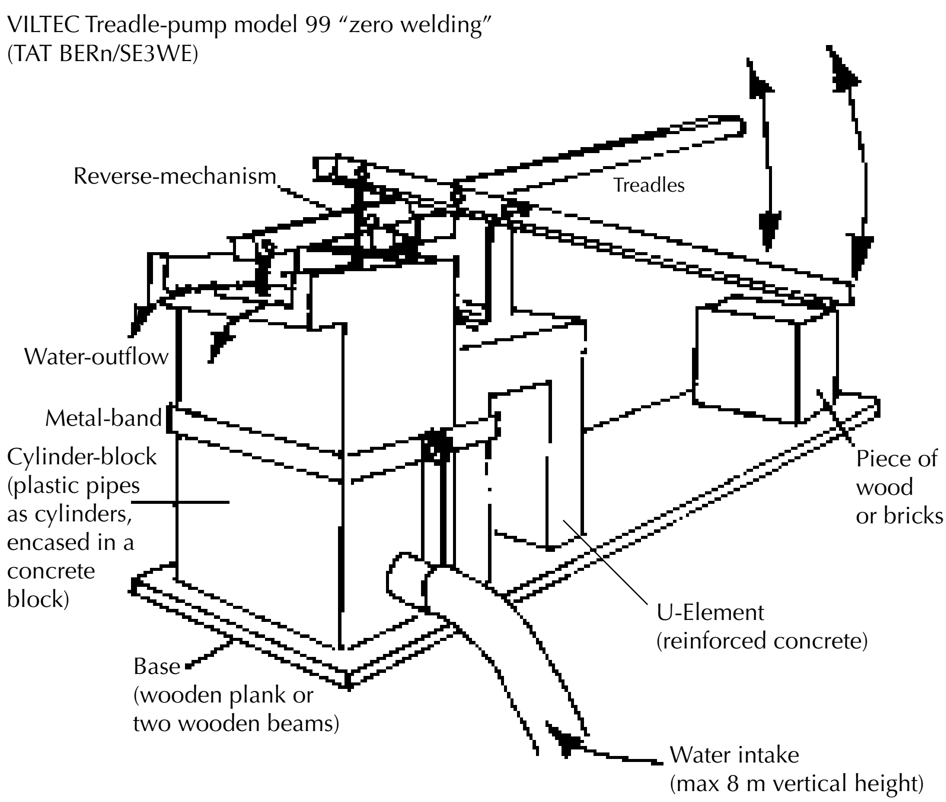


Photo 3.*Treadle pump of zero welding variant.*

Irrigation capacity of treadle pumps

In Ethiopia, peak crop water requirements are about 6 mm/day in the highlands and 8 mm/day in the lowlands. Irrigation efficiency is about 75%. Peak irrigation water requirements are then 8 mm/day (= 80 m^3/ha per day) and 11 mm/day (= 110 m^3/ha per day) in Ethiopian highlands and lowlands, respectively. Considering the human effort demanded to operate a treadle pump, 8 hours per day[2] is a reasonable estimation of maximum daily pumping time. Treadle pumps irrigation capacity (or irrigable area) is given in Table 2. Under most common conditions (head between 2 and 4 m), irrigation capacity of a treadle pump is between 0.2 and 0.6 ha in Ethiopia. However, considering human effort to operate a treadle pump, we recommend to limit irrigated area to 0.5 ha (Shah et al. 2000; Molza-Banda 2006).

Table 2. *Irrigation capacity of treadle pumps assuming a steady useful power of 35 watt 8 hours per day*

Head (m)	1	2	3	4
Discharge (litres/sec)	3.6	1.8	1.2	0.9
Volume pumped in 8 hours (m^3)	102.75	51.38	34.25	25.69
Irrigation capacity (ha) in highland	1.28	0.64	0.43	0.32
Irrigation capacity (ha) in lowland	0.93	0.47	0.31	0.23

Reminder!

For a farmer wanting to irrigate a small area from a shallow water source (less than 4 metres below the surface) a treadle pump may be a good choice.

Ethiopian farmers' labour is not necessarily cheap and plentiful. A very large amount of time and human effort is needed to provide the same power as a small engine. When using a treadle pump, it takes approximately 30 minutes of continuous human effort to pump what a small motorized pump (2.3 kW = 3 hp) can pump in one minute!

Name of pumps	Money maker	Super money maker	Swiss concrete pump
Manufacturer	ApproTEC, Kenya	ApproTEC	Salam vocational Centre, Addis Ababa
Pump body	Metal	Metal	Concrete
Cylinders	Metal	Metal	Plastic
Piston	Metal and rubber	Metal and rubber	Metal and rubber
Other components	Metal and rubber	Metal and rubber	Metal and rubber
Method of joining components	Welding	Welding	Bolts, nuts and screws
Practical max suction head	4 m	4 m	4 m
Max delivery head	0 m	13 m	0 m
Weight (kg)	15	20	60
Manufacturer selling price (USD)	54	75	

Four models of treadle pumps are manufactured in India. They are:

1. 3.5 inch pump (metal barrel) with bamboo treadles (Figure 4)
2. 3.5 inch pump (metal barrel) with metal treadles (Figure 5)
3. 5 inch concrete pump with (PVC sleeves) with wooden pedals (Figure 6)
4. 3.5 inch surface treadle pump (STP) (Figure 7)

The treadle pump is ideal for areas where the water table is high, ranging from 3 m to 7.5 m below the ground. Besides, most of the models of the treadle pump can be used for drawing surface water, such as from ponds, canals, streams and dug wells.

2. In this case, human energy provided each day is about 70 W × 8 hours = 560 Wh.

Figure 4. *Salient features of 3.5 inch pump (metal barrels) with bamboo treadles.*

Figure 5. *Salient features of 3.5 inch treadle pump (metal barrels) with metal treadles.*

Figure 6. *Salient features of 5 inch concrete pump (PVC Sleeves) with wooden pedals.*

Figure 7. *Salient features of 3.5 inch Surface Treadle Pump (STP).*

2.2 Diesel and petrol engines coupled with centrifugal pumps

2.2.1 Diesel and petrol engines

Petrol engines use a spark to ignite the fuel (gasoline) while diesel engines rely on the high temperature achieved by very high compression to ignite diesel oil. The result in practice is that diesel engines are about 3 times heavier than petrol pumps of equivalent power, more robust and with more precise fuel injection components. A diesel engine is therefore more expensive to buy than a comparable petrol engine; however, its working life (in years) will be normally longer than a petrol engine even if petrol engines run fewer hours each day. A diesel engine is also better suited for running many hours a day, day after day. By contrast small petrol engines are designed for running a few hours (up to 5 hours) each day. Usually, petrol engines require more regular maintenance than diesel engines. However, when a serious breakdown occurs to a diesel engine (i.e. troubles with injectors or injection pumps), intervention of a well-qualified mechanic is necessary and spare parts are costly. As fuel oil is cheaper than gasoline, operation costs of diesel engines are lower.

Reminder!

A petrol engine is a good choice when low weight for portability and low purchase price are important and when the pump will be operated only a few hours per day. A diesel engine is recommended when low maintenance and operation costs are important and when the pump is likely to be operated more than five hours each day.

2.2.2 Centrifugal pumps

Centrifugal pumps are the most commonly used engine-powered pumps for small-scale irrigation. They are relatively cheap and very easy to maintain. The centrifugal pump has an impeller with blades, which spins at high speed inside the pump casing (Figure 8). Water is drawn into the pump from the source through a short inlet pipe or suction pipe. As the impeller spins, the water is thrown outwards and is guided towards the outlet or delivery pipe. Centrifugal pumps are described by the diameter (in mm) of the delivery connection pipe where the hose is connected. A rough guide to select a pump in Ethiopia is presented in Table 3. **It is wise to seek advice from an irrigation engineer before selecting a pump.**

Table 3. *Rough guide for pump selection in Ethiopia*

Engine power kW (hp)	Pump size (mm)	Estimated highlands irrigable area	Estimated lowlands irrigable area
1.5 (2)	25	1.5 ha	1.2 ha
3.7 (5)	50	5.0 ha	4.0 ha
5.2 (7)	75	9.0 ha	6.5 ha
6.7 (9)	100	12.0 ha	9.0 ha

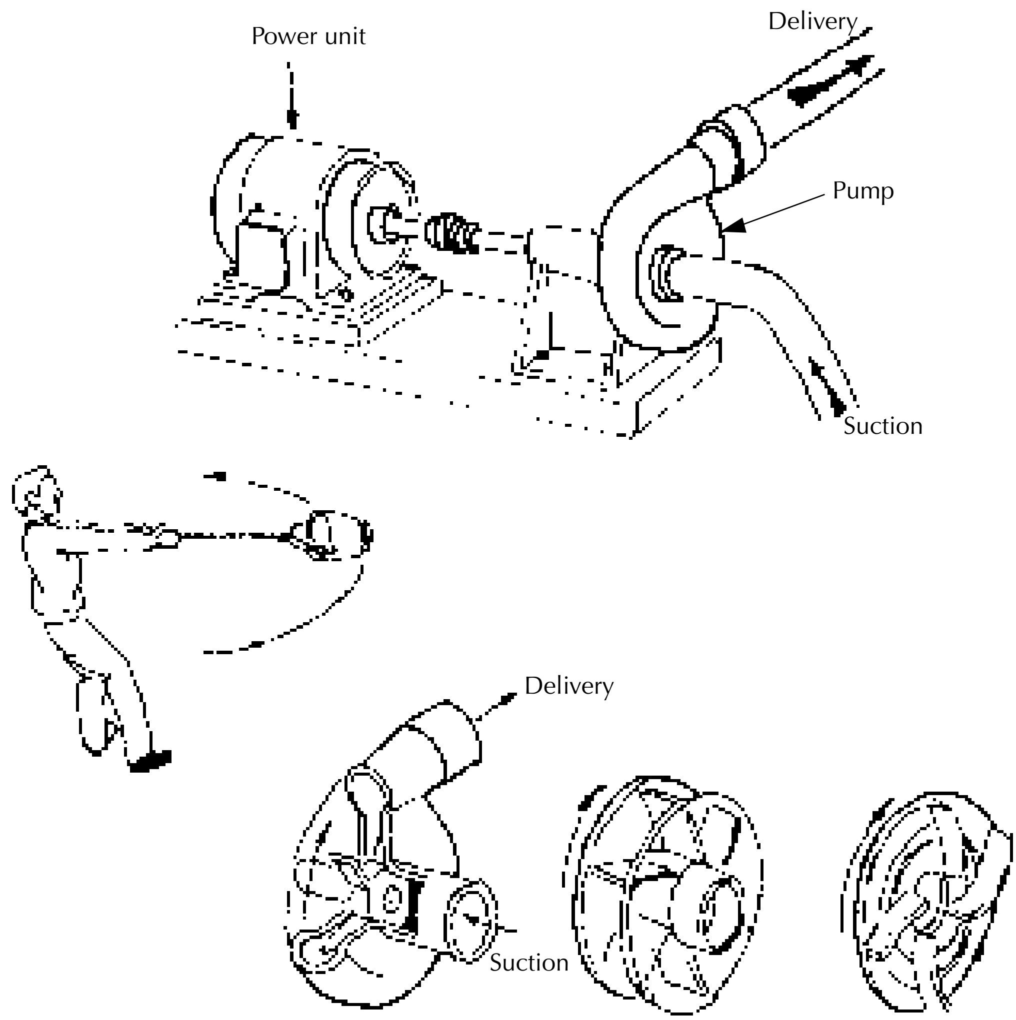


Figure 8. *Motorized centrifugal pumps.*

Irrigable area is estimated assuming irrigation efficiency is 50% and maximum pumping time is 12 hours per day. In practice:

- If actual maximum pumping time is for example 5 hours a day, reduce irrigation capacity by 5/12 ratio.
- An irrigation efficiency of 50% is an acceptable benchmark for surface irrigation with earthen canals. However, due to poor operation and maintenance, irrigation efficiency may be less than 50%. This will reduce irrigation capacity.

Manufacturers produce a range of different impeller designs for any size of pumps. Depending on the impeller design all motorized centrifugal pumps would give their best performance at a specific motor speed, head and f ow discharge. The pump manual will normally give the pump characteristics under the form of a graph showing the relationship between head and discharge at the optimal engine speed.

Adequacy between power/head per discharge and efficiency of centrifugal pumps

Motorized pumps efficiency is the ratio between power used to lift water and mechanical power provided by the motor. Centrifugal pumps are not very appropriate for surface irrigation. Because of global market demand, they are designed to provide relatively high head and low discharge for a given power while low head and large discharge is more suitable for surface irrigation. As there is no practical alternative, some level of inefficiency, i.e. fuel wasting, has to be accepted.

Example 2.1

A pump driven by a 3.7 kW (5 hp) motor is designed to deliver about 14 litres/sec at 18 m of water head. In this case the power delivered to lift water is 2.5 kW (calculated with Equation 3) and efficiency is 68% (= 100 × 2.5 kW/3.7 kW). If farmers need to raise water through a total head of 5 m only, the pump will then give a discharge of 21 litres/sec. The useful power to lift water will then be 1.0 kW and efficiency 27%. In this case, using the same amount of fuel the pump provides less power or, in other words, the pump uses more fuel to provide the same amount of energy.

Pump speed and efficiency

The pumps characteristic curve given by manufacturers assumes that the pump is run at its **optimum design speed**. Diesel or petrol engines driving centrifugal pumps have a throttle to adjust the pump speed and the optimum design speed is usually three-quarters of the maximum throttle. Farmers often run their pumps very slowly to reduce the discharge usually because they find it difficult to manage f ow in the field. In this case inefficiency (waste of fuel) becomes much worse: the pump will use more fuel even though the amount of water pumped is less. A pump gives its best performance at its optimum design speed.

> Reminder!
>
> To avoid wasting fuel:
>
> When selecting a pump, try to have the best possible adequacy between power and required discharge and head. An irrigation engineer who understands pump characteristics may help.
>
> Centrifugal pumps should be operated close to optimum design speed that is usually at three-quarters maximum engine throttle.

2.3 Criteria and tips for selecting irrigation pumps

When dealing with pumping technology, extension officers' job consists mainly in guiding farmers for selecting a technology well adapted to their needs and constraints. Suggested selection criteria are:

- Best possible adequacy between engine power and required discharge and head
- Low purchase cost
- Long working life
- High efficiency of human or fuel energy
- Low operating costs

- Easy access to spare parts at reasonable price and low repair cost
- Portability in case of multiple users in different places or for limiting risk of theft.

Photo 4: *Deep well pump, Kobo Girana Valley Development, Ethiopia (Courtesy, Sileshi B Awulachew).*

Chapter 3 Operation and maintenance of pumps

Chapter objectives:

Upon the completion of this chapter, you will be able to:

- understand suction and delivery head
- explain maintenance of pumps
- describe pumping cost
- determine the sustainability of pump-fed irrigation

3.1 Suction head

Treadle pumps or centrifugal pumps must be located above the water source and the pipe used to draw water from the source into the pump is the suction pipe (Shah et al. 2000 and 2002). The difference in height between the water surface and the pump is the suction head (or suction lift). **Suction head is the most important aspect affecting the operation of a pump.** Pumps do not actually 'suck' water as it is often imagined. A pump takes water from the source by creating a low pressure in the suction pipe. Atmospheric pressure does the rest, pushing down on the water and forcing water up into the suction pipe. At sea level atmospheric pressure is approximately 10 m head of water (= 1 kgf/cm^2). In theory it can push water up to 10 m; **this upper limit applies to all pumps.**

Because of friction losses and the difficulty to create an extremely low pressure, practical limit is 7 m (Figure 9). Even at this limit pumps will have difficulties to operate and discharge will drop. **At high altitudes as in Ethiopian highlands, atmospheric pressure is less than at sea level, practical limit decreases of 1 m for every 1000 m of altitude. At 2000 m above sea level, practical limit is 5 m.**

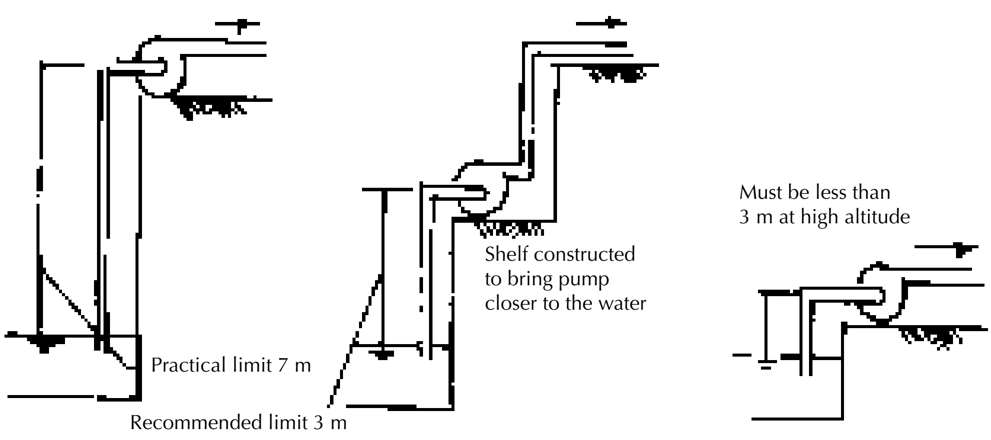


Figure 9. *Suction head limitation.*

Priming a pump

All treadle pumps and most centrifugal pumps have to be primed before starting pumping. Priming the pump simply means that the pumps casing and the suction pipe should be filled with water thus expelling all the air from the pump-system.

> Reminder!
>
> Locate the pump less than 3 metres above water source. It is better to use a pump to 'push' water rather than suck it, keep the pump as close to the water level as possible.

3.2 Suction and delivery pipe

The suction pipe must be stiff-walled to prevent the pipe from collapsing under atmospheric pressure when the pump creates a low pressure inside it. As a consequence, suction pipes are expensive, which is another good reason for keeping the pump close to the water surface. The suction pipe must be sufficiently immersed beneath the water surface so that there is no risk of drawing in air; to do so it may be necessary to dig into the bed of the stream. However, the suction pipe inlet should not be placed on the bed of the water source (stream, lake…) to avoid pumping dirt and mud. The delivery pipe does not have to be stiff-walled, as the water pressure will keep it open. Lay-flat pipes are very common but are not very durable and may be quickly damaged if moved around the farm.

With **treadle pumps**, water is usually released directly from the delivery pipe to the furrows (or on top of the crops for treadle pumps having a delivery pressure). With **motorized pumps**, delivering the full pump discharge directly to the crop beds or furrows is not wise. The flow is usually too strong to be well controlled therefore can be damaging for crops and cause soil erosion. When they see this, farmers reduce the flow by slowing the pump, which is also not wise. It is much better delivering water to a stilling basin located at the highest part of the farm and then dividing and distributing water through small canals to the crop bed or furrows.

> Reminder!
>
> Install pumps close to the water surface.
>
> With motorized pumps:
>
> - It is recommended to deliver water first to a stilling basin located at the highest part of the farm and then distribute water by gravity (canals) to crops.
> - To avoid excessive fuel waste, motorized pumps should run at a speed close to the optimum design speed, i.e. about three-quarters of the maximum motor throttle.
> - When selecting a pump, try to have the best possible adequacy between power and required discharge and head. An irrigation engineer who understands pump characteristics may help.

3.3 Maintenance of pumps

Irrigation pumps and engines should be maintained following the instructions provided in the manufacture's manual. Inform farmers about these instructions through leaflets and training sessions. Try to involve local pumps dealers, spare parts retailers and mechanics in these sessions. Farmers should be trained to carry out routine maintenance tasks such as changing filters and bleeding fuel lines to remove air. Farmers should know reliable mechanics in case of major problems and where to find spare parts at reasonable prices.

3.4 Pumping cost

Farmers should be encouraged to keep a book for registering expenditures to run the pump: cost of fuel, oil (lubricant) and spare parts. Organizing sessions enabling farmers to compare their pumping cost/irrigated ha and pumping costs to their overall production costs would be useful to improve irrigation management.

Table 4 gives theoretical fuel consumption of well-maintained, not too old motorized pumps. As you can see fuel cost of diesel engine are usually much lower as petrol engines. These data can help for your follow-up activities.

Table 4. *Theoretical fuel consumption of well maintained motorized pumps*

Engine power kW (hp)	Diesel engine	Petrol engine
	Consumption of diesel oil (litre/hour)	Consumption of gasoline (litre/hour)
1.5 (3)	0.7	1.7
3.7 (5)	1.7	4.1
5.2 (7)	2.4	5.8
6.7 (9)	3.0	7.4

3.5 Sustainability of pump-fed irrigation

Even properly maintained pumps need replacement at the end of their working life. There are many examples of farmers having abandoned irrigated agriculture because they could not afford to replace their old worn out pump. This particularly occurs when pumps have been donated or subsidized and in group-based irrigation scheme with a relatively large number of farmers, says from experience more than 30. Extension officers should provide guidance and follow-up support to farmers about financial management of irrigation to help them saving money for pump replacement or major breakdown. Seeking advice of financial professionals such as bankers, accountants of cooperative or credit institutions is a good idea.

Reminder

- Saving money for pump replacement or major breakdown is a crucial issue for pump-fed irrigation sustainability
- Irrigation financial management requires skills most farmers don’t have. Hence farmers’ guidance and follow-up is important. Try to involve financial professionals in doing so. In group-based irrigation schemes, difficulty of financial management increases with number of farmers. Maximum group size should be about 30 persons.

In theory, the money to be saved each year should be equal to the cost of the pump divided by its working life expectancy. The latter varies with the conditions of operating the pump. Roughly life expectancy of petrol engine powered pumps is 3–5 years, 6–10 years for a diesel engine. However, more f exible management systems are possible, for instance based on profit made each season or year.

Chapter 4 Water-powered pumps (hydraulic ram)

Chapter objectives:

After reading and understanding this chapter, you will be able to:

- explain operation principles of hydraulic ram
- construct home-made hydraulic ram
- describe factors in design of hydraulic ram
- explain the components of hydraulic ram

A hydraulic ram or impulse pump is a device that uses the energy of falling water to lift a lesser amount of water to a higher elevation than the source (Figure 10). There are only two moving parts, and thus there is little to wear out. Hydraulic rams are relatively economical to purchase and install. They can be built with detailed plans and if properly installed, they can give many trouble-free years of service with no pumping costs. For these reasons, the hydraulic ram is an attractive solution where a large gravity f ow exists. A ram should be considered when there is a source that can provide at least seven times more water than the ram is to pump and the water is, or can be made, free of trash and sand. There must be a site for the ram at least 0.5 m below the water source and water must be needed at a level higher than the source.

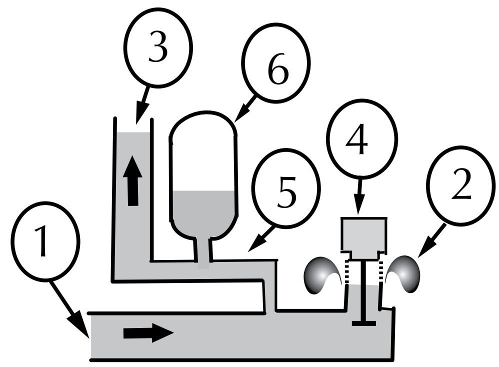
Figure 10. *A hydraulic ram that drives a fountain at the Centre for Alternative Technology.*

4.1 Operation principles and construction

4.1.1 Principles of operation

A hydraulic ram has only two moving parts, a spring or weight loaded 'waste' valve sometimes known as the 'clack' valve and a 'delivery' check valve, making it cheap to build, easy to maintain, and very reliable. In addition, there is a drive pipe supplying water from an elevated source, and a delivery pipe, taking a portion of the water that comes through the drive pipe to an elevation higher than the source. The sequence of its operation is shown below:

Referring to Figure 11, initially, the [4] waste valve is open, the [5] delivery valve is closed. The water in the [1] drive pipe starts to f ow under the force of gravity and picks up speed and kinetic energy until it forces the waste valve closed. The momentum of the water f ow in the supply pipe against the now closed waste valve causes a water hammer, raises the pressure in the pump and opens the delivery valve [5], so some water f ows into the delivery pipe [3]. Since this water is being forced uphill through the delivery pipe rather than it is falling downhill from the source, the f ow slows down and when it reverses the delivery check valve closes. If all water f ow has stopped, the loaded waste valve reopens against the now static head, allowing the process to begin again. A pressure vessel [6] containing air, cushions the hydraulic pressure shock when the waste valve closes, and it also improves the pumping efficiency by allowing a more constant f ow through the delivery pipe.



(1) Inlet — drive pipe; (2) Free f ow at waste valve; (3) Outlet — delivery pipe; (4) Waste valve; (5) Delivery check valve; and (6) Pressure vessel.

Figure 11. *Sequence of operation of a hydraulic ram.*

The optimum length of the drive pipe is 5 to 12 times the vertical distance between the source and the pump or 500 to 1000 times the diameter of the delivery pipe whichever is less. This length of drive pipe typically results in a period between pulses of 1 to 2 seconds. A typical efficiency is 60%, but up to 80% is possible. The drive pipe is ordinarily straight but can be curved or even wound in a spiral. The main requirement is that it is inelastic, strong and rigid as otherwise it would greatly diminish the efficiency.

4.1.2 Home-made hydraulic ram pump

The information in Figure 12 is provided as a service to those wanting to build their own hydraulic ram pump at home. The data from our experiences with one of these home-made hydraulic ram pumps is listed in Table 5.

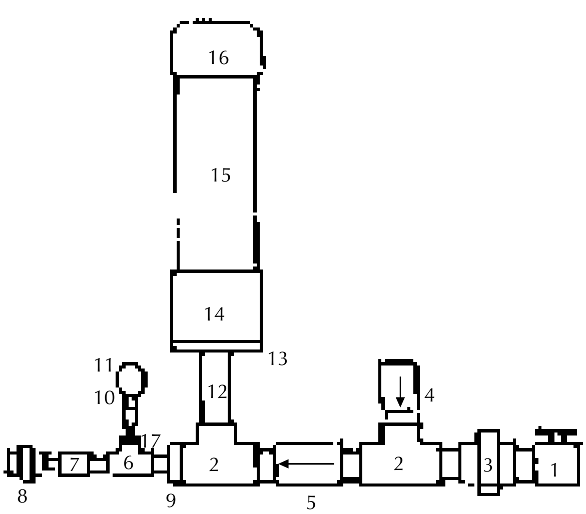


Figure 12. *Home-made hydraulic ram.*

Table 5. *Materials for Figure 12*

1	1 1/4″ valve	10	1/4″ pipe cock
2	1 1/4″ tee	11	100 psi gauge
3	1 1/4″ union	12	1 1/4″ × 6″ nipple
4	1 1/4″ brass swing check valve (picture)	13	4″ × 1 1/4″ bushing
5	1 1/4″ spring check valve	14	4″ coupling
6	3/4″ tee	15	4″ × 24″ PR160 PVC pipe
7	3/4″ valve	16	4″ PVC glue cap
8	3/4″ union	17	3/4″ × 1/4″ bushing
9	1 1/4″ × 3/4″ bushing		

All connectors between the fittings are threaded pipe nipples — usually 2″ in length or shorter. This pump can be made from PVC fittings or galvanized steel. In either case, it is recommended that the 4″ diameter fittings be PVC fittings to conserve weight.

Conversion note: 1″ (1 inch) = 2.54 cm; 1 PSI (pound/square inch) = 6.895 KPa or 0.06895 bar; 1 gallon per minute = 3.78 litre per minute. PR160 PVC pipe is PVC pipe rated at 160 psi pressure.

The samples for the installations are shown in Figures 13, 14 and 15.

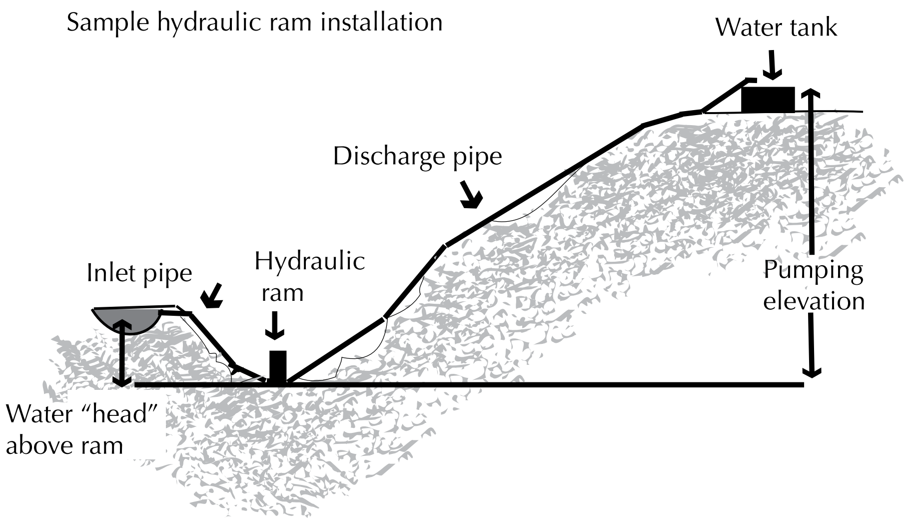


Figure 13. *This installation is the 'normal' ram system where the inlet pipe is less than the maximum length allowed. No stand pipe or open tank is required.*

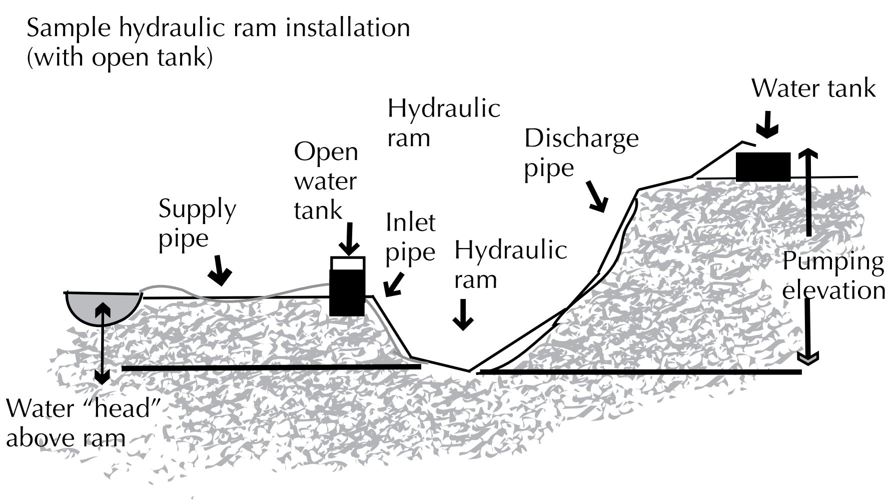


Figure 14. *This installation is one option used where the inlet pipe is longer than the maximum length allowed. The open water tank is required to allow dissipation of the water hammer shock wave.*

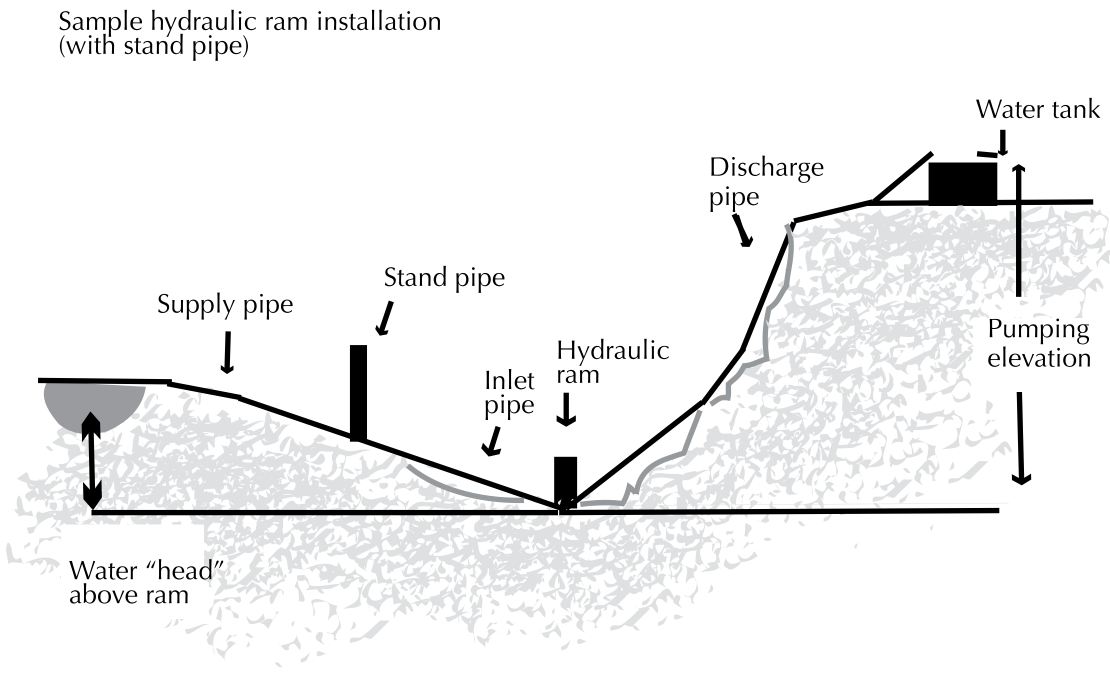


Figure 15. *This installation is another option used where the inlet pipe is longer than the maximum length allowed. The stand pipe (open to atmosphere at the top) is required to allow dissipation of the water hammer shock wave.*

4.2 Factors in design

Before a ram can be selected, several design factors must be known.

1. The difference in height between the water source and the pump site (called vertical fall).
2. The difference in height between the pump site and the point of storage or use (lift).
3. The quantity (Q) of flow available from the source.
4. The quantity of water required.
5. The length of pipe from the source to the pump site (called the drive pipe).
6. The length of pipe from the pump to the storage site (called the delivery pipe).

Once this information has been obtained, a calculation can be made to see if the amount of water needed can be supplied by a ram. The formula is:

$$D = (S \times F \times E)/L$$

where:

D = amount delivered in litres per 24 hours
S = quantity of water supplied in litres per minute
F = the fall or height of the source above the ram in metres
E = the efficiency of the ram (for commercial models use 0.66, for home built use 0.33 unless otherwise indicated)
L = the lift height of the point of use above the ram in metres.

Table 6 solves this formula for rams with efficiencies of 66 percent, a supply of 1 litre per minute, and with the working fall and lift shown in the table. For supplies greater than 1 litre/minute, simply multiply by the number of litres supplied.

Table 6. *Ram performance data for a supply of 1 litre/minute*

Working fall (m)	Litres delivered over 24 hours Lift—Vertical height to which water is raised above the ram (m)											
	5	7.5	10	15	20	30	40	50	60	80	100	125
1.0	144	77	65	33	29	19.5	12.5					
1.5		135	96.5	70	54	36	19	15				
2.0		220	156	105	79	53	33	25	19.5	12.5		
2.5		280	200	125	100	66	40.5	32.5	24	15.5	12	
3.0			260	180	130	87	65	51	40	27	17.5	12
3.5				215	150	100	75	60	46	31.5	20	14
4.0				255	173	115	86	69	53	36	23	16
5.0				310	236	155	118	94	71.5	50	36	23
6.0					282	185	140	112	93.5	64.5	47.5	34.5
7.0						216	163	130	109	82	60	48
8.0							187	149	125	94	69	55
9.0							212	168	140	105	84	62
10.0							245	187	156	117	93	69
12.0							295	225	187	140	113	83
14.0								265	218	167	132	97
16.0									250	187	150	110
18.0									280	210	169	124
20.0										237	188	140

4.3 Components of hydraulic ram

A hydraulic ram installation consists of a supply, a drive pipe, the ram, a supply line and usually a storage tank (see Figures 13–16).

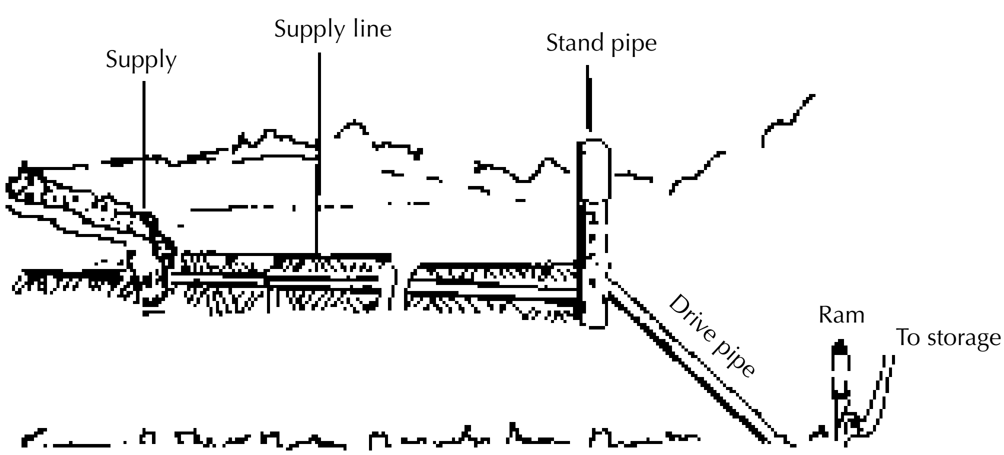


Figure 16. *Ram pump remote from source.*

Supply. The intake must be designed to keep trash and sand out of the supply since these can plug up the ram. If the water is not naturally free of these materials, the intake should be screened or a settling basin provided. When the source is remote from the ram site, the supply line can be designed to conduct the water to a drive pipe as shown in Figure 16. The supply line, if needed, should be at least one pipe diameter larger than the drive pipe.

Drive pipe. The drive pipe must be made of a non-f exible material for maximum efficiency. This is usually galvanized iron pipe, although other materials cased in concrete will work. In order to reduce head loss due to friction, the length of the pipe divided by the diameter of the pipe should be within the range of 150–1000. Table 7 shows the minimum and maximum pipe lengths for various pipe sizes.

Table 7. *Range of drive pipe lengths for various pipe diameters*

Drive pipe size (mm)	Length (metres)	
	Minimum	Maximum
13	2	13
20	3	20
25	4	25
30	4.5	30
40	6	40
50	7.5	50
80	12	80
100	15	100

The drive pipe diameter is usually chosen based on the size of the ram and the manufacturer's recommendations as shown in Table 8. The length is four to six times the vertical fall.

Table 8. *Drive pipe diameters by hydram manufacturer's size number*

Hydram size	1	2	3	3.5	4	5	6
Pipe size (mm)	32	38	51	63.5	76	101	127

Ram. Rams can be constructed using commercially available check valves or by fabricating check valves. They are available as manufactured units in various sizes and pumping capacities. Rams can be used in tandem to pump water if one ram is not large enough to supply the need. Each ram must have its own drive pipe, but all can pump through a common delivery pipe as shown in Figure 17.

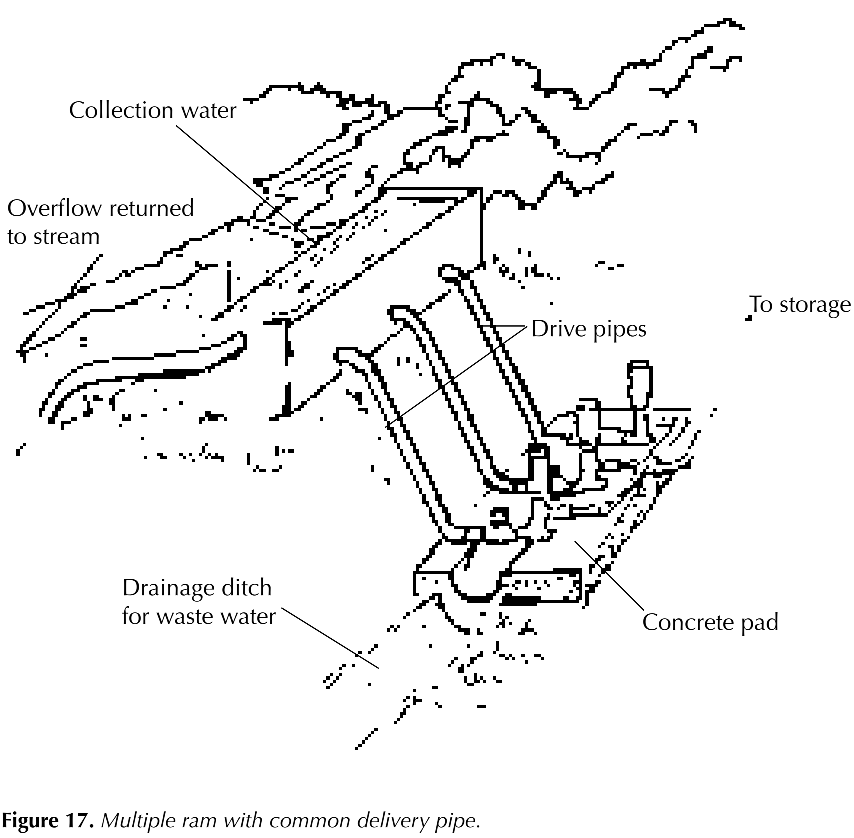


Figure 17. *Multiple ram with common delivery pipe.*

When installing the ram, it is important that it be level, securely attached to an immovable base, preferably concrete, and that waste-water be drained away. The pump cannot operate when submerged. Since the ram usually operates on a 24-hour basis the size can be determined for delivery over a 24-hour period. Table 9 shows hydraulic ram capacities for one manufacturer's hydrams.

Table 9. *Hydram capacity by manufacturer's size number*

	Size of hydram								
	1	2	3	3.5	4	5X	6X	5Y	6Y
Volume of drive water needed (litres/min)	7–16	12–25	27–55	45–96	68–137	136–270	180–410	136–270	180–410
Maximum lift (m)	150	150	120	120	120	105	105	105	

Delivery pipe. The delivery pipe can be of any material that can withstand the water pressure. The size of the line can be estimated using Table 10.

Table 10. *Sizing the delivery pipe*

Delivery pipe size (mm)	Flow (litres/min)
30	6–36
40	37–60
50	61–90
80	91–234
100	235–360

Storage tank. This is located at a level to provide water to the point of use. The size is based on the maximum demand per day.

Chapter 5 Wind powered pumps

Chapter objectives:

After reading and understanding this chapter, you will be able to:

- describe and adopt wind-powered water pumps for livestock watering
- explain kinds of windmills
- choose a location for a windmill
- estimate water delivered by wind-powered pump
- know kinds of pumps available for use with windmills

5.1 Wind-powered water pumps for livestock watering

Wind power is a non-polluting renewable energy resource that can be harnessed where access to power lines is not practical. There are three types of wind power systems. Two of them use mechanical power to pump water, while the third converts wind power to electrical energy.

Mechanical—piston pump—This system converts rotary wind power to vertical motion, using a snake rod and a piston pump to lift water.

Mechanical—air lift pump—This system uses wind power to charge a compressor that pumps air to lift water.

Electrical pump—The electrical pumping system channels the energy generated directly to the water pump, and/or to a battery storage system. The system design will depend on:

- your specific energy needs
- whether a battery storage system is required
- the amount of wind available to the site.

Batteries can account for more than 20% of the total capital investment, so they are a key factor if you are considering an electrical pumping system. Water supplies such as wells and dugouts can often be developed on the open range. However, the availability of power supplies on the open range is often limited, so some alternate form of energy is required to convey water from the source to a point of consumption. Wind energy is an abundant source of renewable energy that can be exploited for pumping water in remote locations, and windmills are one of the oldest methods of harnessing the energy of the wind to pump water (Figure 18).

5.2 Kinds of windmills

There are generally considered to be two types of windmills, with the classification depending on the orientation of the axis of rotation of the rotor. Vertical-axis wind turbines are efficient and can obtain power from wind blowing in any direction, whereas horizontal-axis devices must be oriented facing the wind to extract power. Most windmills for water-pumping applications are of the horizontal-axis variety, and have multi-bladed rotors that can supply the high torque required to initiate operation of a mechanical pump. Windmills can also be used to generate electricity, but electricity-generating units usually consist of vertical-axis rotors or high-speed propellor rotors, due to the requirement for low starting torques. Figure 18 illustrates a typical water-pumping windmill.

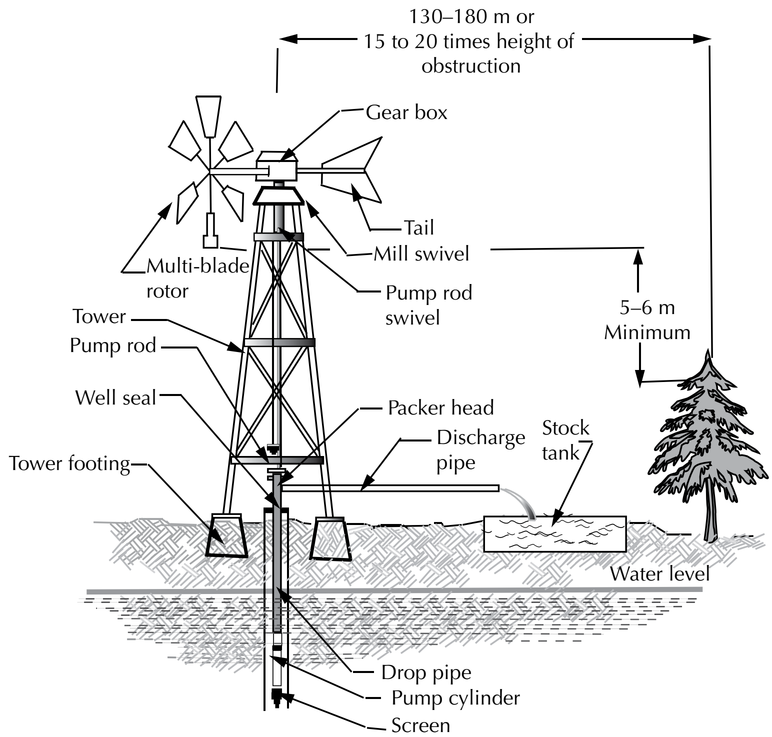


Figure 18. *Typical windmill water pump.*

5.3 Choosing location for a windmill

The primary consideration in choosing a site for a windmill is whether there is sufficient wind for such a device to be feasible. Obtaining site-specific measurements of wind speed and duration during the period over which water pumping is required is the only reliable way of determining whether a wind-powered pumping unit will be a viable option. To take such measurements, an anemometer is required (Figure 19).

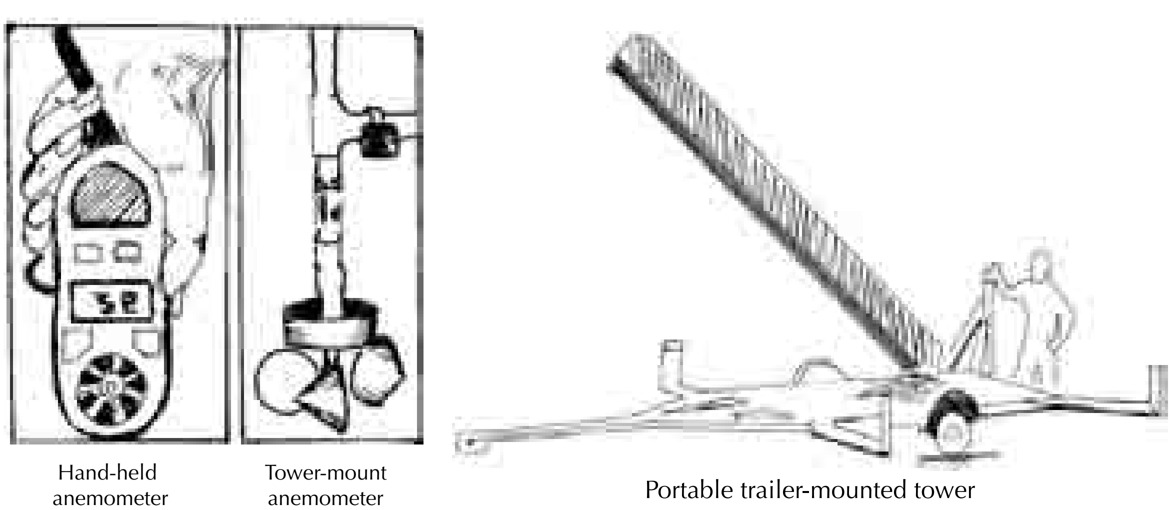


Figure 19. *Anemometer for measuring wind speed.*

Economical hand-held anemometers are available, but their use requires that a considerable amount of time be spent on site to establish meaningful records. A better way of gathering wind data would be to mount an anemometer (with an automated data recording device) on a tower similar in height to the proposed windmill for the entire period of interest.

Typically television or radio antenna towers can be used, and some are available as portable, trailer-mounted units.

Windmills used to generate electricity to power an electrical pump can be located away from the pumping unit, and windmills that power an air compressor, which operates an airlift pump, can also be located away from the pump. However, most windmills are designed to operate a reciprocating piston-type pump and must be located directly over the water source (usually a well).

To ensure that the windmill receives a free f ow of air from all directions, the rotor of a windmill should be located at least 5 to 6 m (15 to 20 feet) higher than any obstruction within about 130 to 180 m (450 to 600 feet) of the windmill site. In fact, wind speeds generally increases with altitude, so the tower should be as high as reasonably possible, regardless of the presence of obstructions. Topographic effects, such as confined draws and hills, should also be considered.

5.4 Water delivered by wind-powered pump

The amount of water a wind-powered water pumping system can deliver depends on the speed and duration of the wind, the size and efficiency of the rotor, the efficiency of the pump being used, and how far the water has to be lifted. The power delivered by a windmill can be determined from the following equation:

$$P = 0.0109 D^2 V^3 \eta$$

where P is power in watts, D is the rotor diameter in metres, V is the wind speed in kilometres per hour, and η is the efficiency of the wind turbine. As can be seen from this expression, relatively large increases in power result from comparatively small increases in the size of the rotor and the available wind speed; doubling the size of the rotor will result in a four-fold increase in power, while doubling the wind speed will result in an eight-fold increase in power. However, the efficiency of wind turbines decreases significantly in both low and high winds, so the result is that most commercially-available windmills operate best in a range of wind-speeds between about 15 km/hr and 50 km/hr.

5.5 Kinds of pumps available for use with windmills

If the windmill is used to generate electricity to power an electrical pump, it will probably be necessary to store the electricity in batteries due to the variability in generation. Therefore, a pump powered by an electrical motor for use in conjunction with a windmill that generates electricity should have a Direct Current (DC) motor. For such systems, it is important to use good-quality deep-cycle batteries and to incorporate electrical controls such as blocking diodes and charge regulators to protect the batteries.

The most common type of pump used with windmills is the positive-displacement cylinder pump driven by a reciprocating rod connected to a gearbox at the windmill rotor (Figure 20). The performance of these pumps can be enhanced through the addition of springs, cams and counterweights that alter the stroke cycle and off-set the weight of the drive rod, thereby reducing the starting torque and allowing the system to perform better in light winds.

An alternative to the traditional cylinder pump is the airlift pump (Figure 21). The air-lift pump is a type of deep-well pump, sometimes used to remove water from mines. It can also be used to pump slurry of sand and water or other 'gritty' solutions. In its most basic form this pump has no moving parts, other than an air compressor driven by the windmill. The efficiency of the air compressor is a prime factor in determining the overall efficiency of the pump. Compressed air is piped down the well to a foot piece attached to the discharge pipe. As air is discharged into the water column in the discharge pipe, a two-phase mixture of air and water is formed that is less dense than the surrounding water in the well. This apparent density difference is what causes water to rise in the discharge pipe.

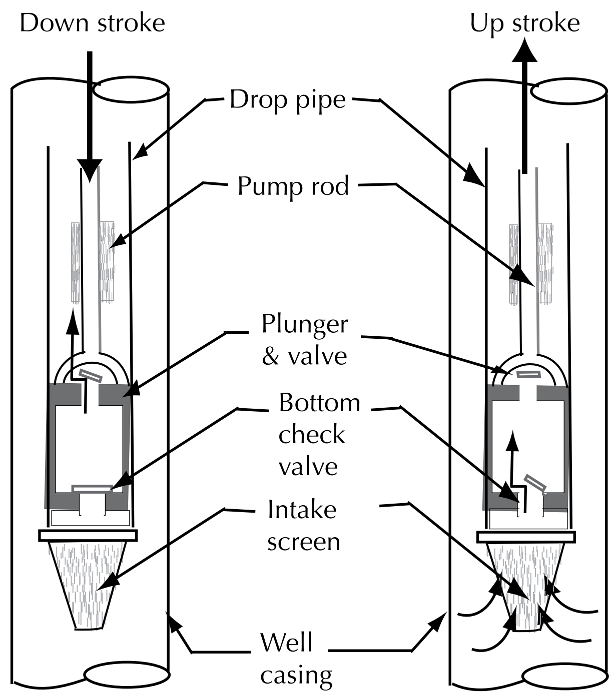


Figure 20. *Typical windmill pump cylinder.*

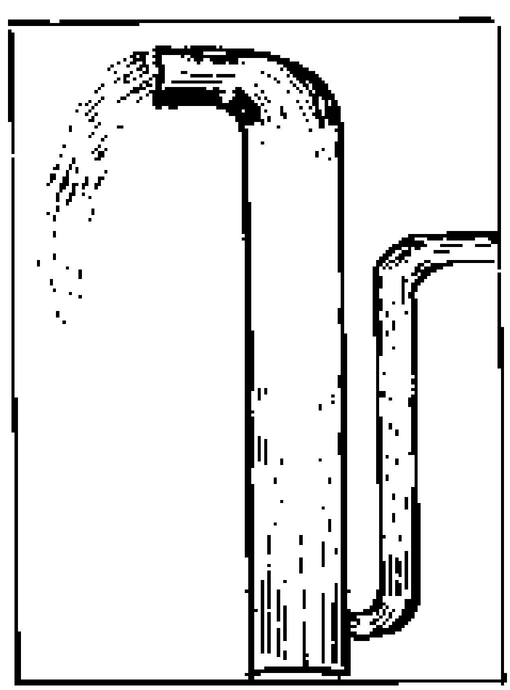


Figure 21. *Air-lift pump.*

Airlift pumps can lift water at rates between 20 to 2000 gallons per minute, up to about 750 feet. The discharge pipe must be placed deep into the water, from 70% of the height of the pipe above the water level (for lifts up to 20 feet) down to 40% for higher lifts. This is the most significant drawback to airlift pumps, because many wells do not have the required depth of standing water. An advantage to this kind of pump is that the windmill can be located away from the well, and the windmill/air-compressor combination can also be used to aerate dugouts.

Chapter 6 Solar-powered pumps

Chapter objectives:

After reading and understanding this chapter, you will be able to:

- explain working principles of solar-powered pumps
- install solar pumps
- know some types of solar pumps such as small solar pump with fountain head, large solar fountain pump, submersible solar pump, solar pool pump system (centrifugal surface pump), and solar pond pump system

A solar powered pump is a pump running on the power of the sun. A solar powered pump can be more environmental friendly and economical in its operation compared to pumps powered by an internal combustion engine (ICE). A solar powered pump consists of two parts, namely (a) the actual pump, and (b) the energy source being powered by the sun. It can provide a reliable water supply and eliminate the installation of power lines in environmentally sensitive areas. Because power lines are not needed, there is no need to spray chemicals around the base of poles. Solar-powered pumps rely on photovoltaic (PV) panels or modules—composed of silicone cells connected in parallel or series—which generate electricity when sunshine strikes the surface of the cells. Power modules are available in various wattages and voltages. PV panels pose little or no threat to the environment, wildlife and people. Because PV systems must be custom designed to user and site characteristics, costs vary. Prices range from USD 900 to more than USD 6000.

A combined solar and wind powered pump system is designed for getting water to remote rural locations and is used extensively worldwide. The main application is for getting water from wells or boreholes for livestock or drinking water. Solar and wind powered pumps can also be used for surface water management and the irrigation of fields.

6.1 Working principles of solar-powered pumps

The process is simple, the pump is submersible and is lowered into the water source and it is powered by a direct drive renewable energy system: either a wind turbine or solar panels (PV). The solar panels or wind turbine produce electricity, which is passed through a control unit and can be connnected to batteries as well, and this drives the pump. The pump can be powered by wind turbines, solar panels, generators and a combination of some or all three.

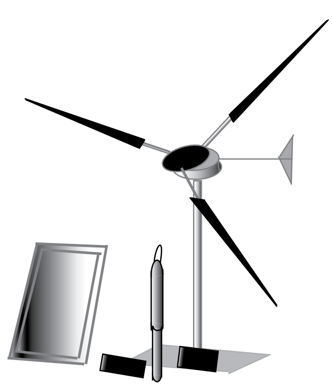


Figure 22. *Combination of solar and wind-powered pumps.*

6.2 Solar pump installations

Solar PV water pumping systems are used for irrigation and drinking water in India. The majority of the pumps are fitted with a 200–3000 watt motor and is powered with 1800 Wp PV arrays, which can deliver about 140 thousand litres of water/day from a total head of 10 metres. By the 30th of September 2006, a total of 7068 solar PV water-pumping systems have been installed.

6.3 Some examples of solar pumps

(A) Small solar pump with fountain head

A small solar pump with fountain head is powered by direct sunlight that is gathered by the solar panel (Figure 23). There is no need for batteries or wiring. It includes three different fountain heads for different fountain shapes. The solar pump has an extra-long cord that allows the solar panel to be placed up to 4.5 m from the fountain.

Figure 23. *Small solar pump with fountain head.*

(B) Large solar AC fountain pump

These powerful, compact, solar- and AC-powered pumps are easy to set up yourself (Figure 24). Not only do they include a separate solar panel you stake into the ground where sunlight is most accessible, it also comes with a UL-listed AC transformer and jack so you can power the fountain even at night. It includes 4.5 m-long cord (from solar panel to pump), adjustable solar panel spike, assorted spray nozzles, and LED accent light.

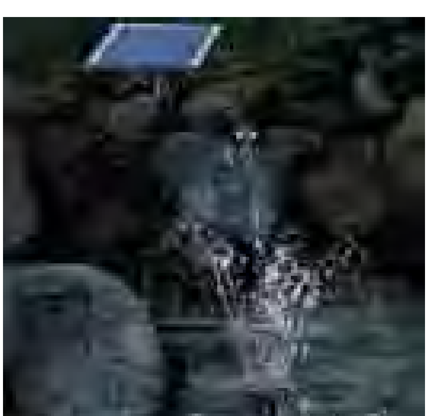


Figure 24. *Large solar AC fountain pump.*

(C) Submersible solar pump

A submersible solar pump is directly powered by solar panels, thus requiring no batteries. When the sun shines, the variable speed DC brushless pump will start pumping and continue pumping until there is insufficient sun. As an option the solar panels can be mounted on a mechanical sun tracking system that will provide maximum output from the solar panels.

Water can be pumped from as deep as 240 metres and systems can be configured to suit your daily water needs and lift requirements.

Application:

- Drinking water supply
- Livestock watering
- Pond management
- Irrigation
- Almost any other application you can think of

Characteristics:

- Lifts up to 240 m
- Flow rate upto 11.0 m^3/h
- Simple installation
- Maintenance-free
- High reliability and life expectancy
- Cost-effective pumping

(D) Solar pool pump system (Centrifugal surface pump)

A solar pool pump system is shown in Figure 25.

Application:

- Swimming pool water circulation through a filter system and thermal collectors
- Pond management
- Irrigation
- Aquariums
- Fish farms

Characteristics:

- Flow rate upto 15.0 m^3/h
- Maintenance-free thanks to brushless DC motor
- Excellent efficiency

Components and features:

- Controller PS 600
- Controlling of the pump system and monitoring of the operating states
- Mounted at surface (no submerged electronic parts)
- Two control inputs for well probe (dry running protection), f oat or pressure
- Switches, remote control etc.

- Automatic reset 20 minutes after well probe turns pump off
- Protected against reverse polarity, overload and high temperature
- Speed control, maximum pump speed adjustable to reduce f ow rate to approximately 30%
- Solar operation: integrated MPFT (Maximum Power Point Tracking)
- Battery operation: low voltages disconnect and restart after battery has recovered
- Maximum efficiency 92% (motor ÷ controller)
- Motor ECDRIVE 600 BADU Top
- Brushless maintenance-free DC motor
- Pump End (PE) BADU top 12
- Monoblock-type pump with integrated strainer tank
- Bellow mechanical seal is mounted on a plastic shaft protected sleeve
- Motor/pump shaft has no contact with f uid
- Total electric separation
- Strainer capacity approximately 3 litres
- Strainer basket mesh size approximately 3.2 × 2.6 mm

Figure 25. *Solar pool pump.*

(E) Solar pond pump system

Solar pond pumps allow free operation by using solar energy; independent of power grids anywhere sunlight is available (Figure 26). It is environmentally friendly using sunlight as an alternate energy source. The high quality module makes solar powered fountains possible until sunset and with the addition of a battery system operation can be extended.

(a)

Figure 26. *Solar pond pump with (a) solar panels; and (b) the pump.*

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Module 5 – Part I

Irrigation methods: Surface irrigation—Options for smallholders

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Chapter 1 Furrow-basin irrigation

Chapter objectives:

Upon the completion of this chapter, you will be able to:

- identify when to use furrow-basin irrigation
- layout furrow-basin irrigation
- irrigate furrow basins
- use the planting techniques of furrow-basin irrigation

1.1 When to use furrow-basin irrigation

Furrow-basin irrigation is the most suitable irrigation method for smallholder farmers, except rice growers. Unlike basin or furrow irrigation, farmers can do levelling manually. Field irrigation efficiency is high at between 0.7% and 0.8%. Furrow basins are labour intensive; hence this method is not recommended on large farms (Adeoti et al. 2006; IWMI 2006). Furrow-basin irrigation is particularly suitable for vegetables and other crops that would be damaged if water covered their stem or crown (Namara et al. 2005; IWMI 2006; Mloza-Banda 2006). Flat or gentle slopes are preferred for furrow-basin irrigation. If slope exceeds 0.5% then levelling is necessary. Furrows can be used on most soil types. However, as with all surface irrigation methods, very coarse sands are not recommended, as percolation losses can be high.

1.2 Layout

Ridges are made within a basin and plants are grown in rows (Figure 1). The distance between ridges equals the required row distance of the crop (Figure 2).

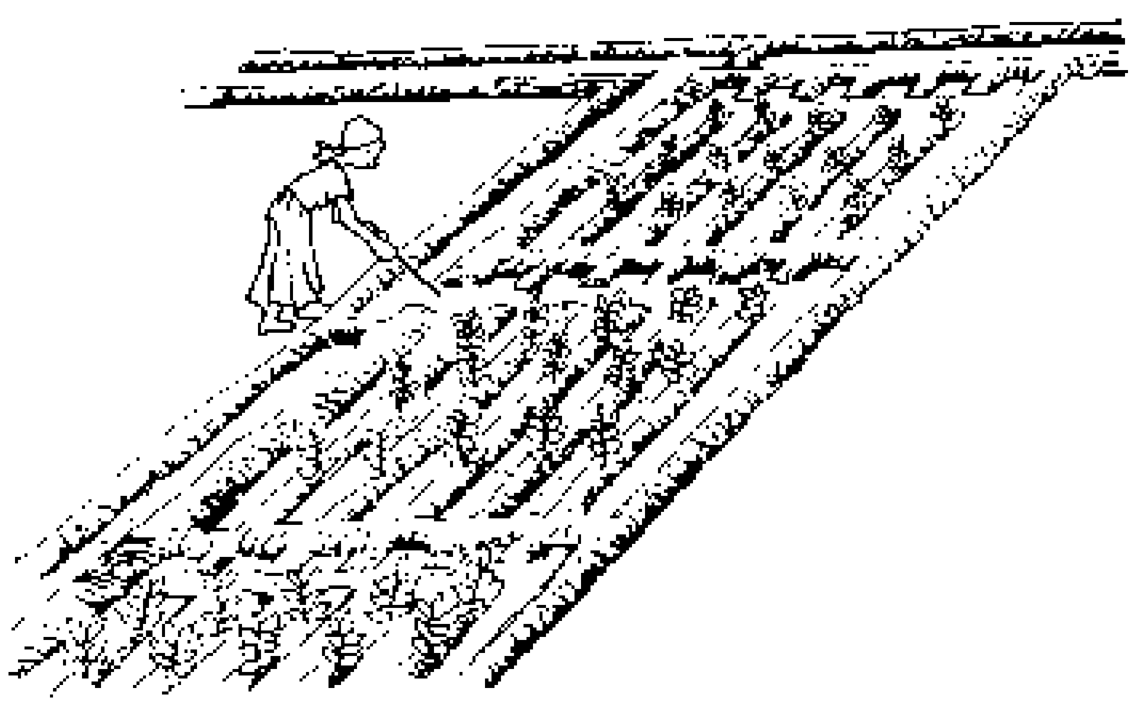

Figure 1. *Layout of furrow-basin irrigation.*

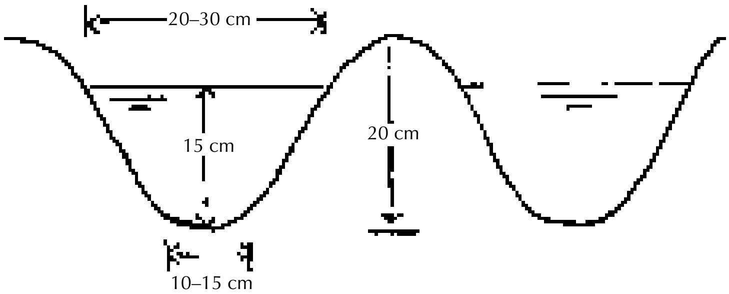

Figure 2. *Dimensions of a furrow and a ridge.*

1.3 Irrigating furrow basins

Water is supplied by making a break in the feeder canal. Discharge at plot gate should be between 3 litres/sec and 5 litres/sec to allow farmers to manipulate water efficiently.

1.4 Planting techniques

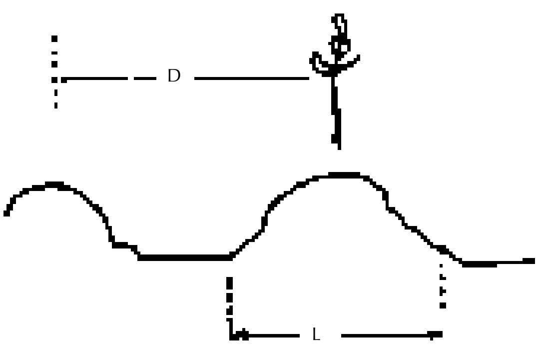

Figure 3. *Planting technique 2: Planting crops on top of the ridge.*

Table 1 *Width of ridge (L) and distance between furrows (D)*

Crops	L	Distance within row
Cabbage	50 cm	30 – 40 cm
Potato	90 cm	30 cm
Sweet potato	90 cm	40 cm
Tomato	100 cm	30 cm
Pepper	90 cm	25 cm

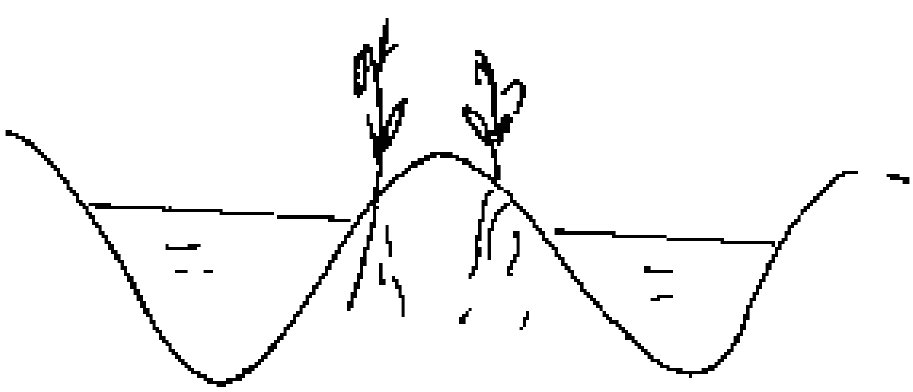

Figure 4. *Planting technique 2: Planting in the sides of the ridge.*

Table 2. *Crops planted on the sides of the ridge*

Crops	D	Distance within row
Carrot	30 cm	3 cm
Beans	40 cm	30 cm
Garlic	30 cm	5–10 cm
Onion	30 cm	5–7 cm
Pea	30 cm	5 cm
Shallot	30 cm	3 cm

Chapter 2 Basin irrigation

Chapter objectives:

After reading and understanding this chapter, you will be able to:

- identify when to use basin irrigation
- design basins
- layout basins
- construct basins
- irrigate basins
- maintain the basins

2.1 When to use basin irrigation

Basin irrigation is suitable for many field crops (Hansen et al. 1980; Garg 1989; Shah et al. 2002). Paddy rice grows best when its roots are submerged in water and so basin irrigation is the best method to use for this crop. Other crops, which are suited to basin irrigation include: pastures (e.g. alfalfa, clover); trees (e.g. citrus, banana); cereals (e.g. maize, wheat, barley) etc. Basin irrigation is generally not suited to crops, which cannot stand in wet or waterlogged conditions for periods longer than 24 hours. These are usually root and tuber crops such as potatoes, cassava, beet and carrots, which require loose, well-drained soils.

The flatter the land surface, the easier it is to construct basins. On flat land only minor levelling may be required to obtain level basins. It is also possible to construct basins on sloping land, even when the slope is quite steep. Level basins can be constructed like the steps of a staircase; these are called terraces.

Soil types those are suitable for basin irrigation depends on the crop grown. A distinction has to be made between rice and non-rice or other crops.

Paddy rice is best grown on clayey soils, which are almost impermeable and percolation losses are low. Rice could also be grown on sandy soils but percolation losses will be high unless a high water table can be maintained (Michael and Pandya 1972). Such conditions sometimes occur in valley bottoms. Although most other crops can be grown on clays, loamy soils are preferred for basin irrigation so that water logging (permanent saturation of the soil) can be avoided. Coarse sands are not recommended for basin irrigation, due to the high infiltration rate, which means that percolation losses can be high. Also soils that form a hard crust when dry (capping) are not suitable.

2.2 Basin layout

Basin layout not only refers to the shape and size of basins but also to the shape and size of the bunds (Michael and Pandya 1972; Hansen et al. 1980; Garg 1989; Shah et al. 2002; IWMI 2006). What is the shape of the basin: square, rectangular or irregular? What is the size of the basin: 10, 100, 1000 or 10,000 m^2? How high should the bund be: 10, 50 or 100 cm? What is the shape of the bund? These aspects are discussed in the following sections.

2.2.1 Shape and size of basins

The shape and size of basins are determined by the land slope, the soil type, the available stream size (the water flow to the basin), the required depth of the irrigation application and farming practices. The main limitation on the width of a basin is the land slope. If the land slope is steep, the basin should be narrow; otherwise too much earth movement will be needed to obtain level basins. Table 3 provides some guidance on the maximum width of basins or terraces, depending on the land slope.

Table 3. *Approximate values for the maximum basin or terrace width (m)*

Slope (%)	Maximum width (m)	
	Average	Range
0.2	45	35–55
0.3	37	30–45
0.4	32	25–40
0.5	28	20–35
0.6	25	20–30
0.8	22	15–30
1.0	20	15–25
1.2	17	10–20
1.5	13	10–20
2.0	10	5–15
3.0	7	5–10
4.0	5	3–8

Three other factors, which may affect basin width, are the depth of fertile soil, method of basin construction, and agricultural practices. If the topsoil is shallow, there is a danger of exposing the infertile subsoil when the terraces are excavated. This can be avoided by reducing the width of basins and limiting the depth of excavation. The size of basins depends not only on the slope but also on the soil type and the available water flow to the basins. The relationship between soil type, stream size and size of the basin is given in Table 4. Values are based on practical experience, and have been adjusted in particular to suit small-scale irrigation conditions.

Table 4. *Suggested maximum basin areas (m^2) for various soil types and available stream sizes (litre/sec)*

Stream size (litre/sec)	Sand	Sandy loam	Clay loam	Clay
5	35	100	200	350
10	65	200	400	650
15	100	300	600	1000
30	200	600	1200	2000
60	400	1200	2400	4000
90	600	1800	3600	6000

Example of how to estimate basin sizes

Question: Estimate the dimensions of basins, when the soil type is a deep clay loam and the land slope is 1%. As basin construction is mechanized, the terraces should be as wide as possible. The available stream size is 25 litres/sec.

Answer: From Table 1 the maximum basin or terrace width for a slope of 1% is 25 m (range 15–25 m).

From Table 2 the maximum basin size for a clay loam soil and an available stream size of 25 litres/sec is 1000 m^2.

If the total basin area is 1000 m^2 and the width is 25 m, the maximum basin length is 1000/25 = 40 m.

Note: This example shows how to estimate the maximum basin dimensions. This basin can be made smaller than this if required and still be irrigated efficiently with the available stream size.

The size of the basin is also influenced by the depth (in mm) of the irrigation application. If the required irrigation depth is large, the basin can be large. Similarly, if the required irrigation depth is small, then the basin should be small to obtain good water distribution. The size and shape of basins can often be limited by farming practice. Many farms in Ethiopia are very small and cultivation is by hand. In these circumstances basins are usually small as they are easy to level and efficient irrigation can be attained with relatively small stream sizes. On large mechanized farms, basins are generally made as large as possible to provide large uninterrupted areas for machine movements. On these large farms, basin dimensions are chosen to be multiples of the width of the machines used, so as to use the equipment as efficiently as possible. Other reasons to make basins as large as possible are that less land is wasted in this way (less bunds) and large stream sizes and a relatively large application depth can be used.

The shape of the basin can be square, rectangular or irregular. The slope determines the shape. On steep and irregular sloping lands, the basins may be long and narrow. The long side of the basin is along the contour line. If the slope and thus the contour line is irregular, the shape of the basin will also be irregular.

In summary

Basins should be small if the:

1. Slope of the land is steep
2. Soil is sandy
3. Stream size to the basin is small
4. Required depth of the irrigation application is small
5. Field preparation is done by hand or animal traction.

Basins can be large if the:

1. Slope of the land is gentle or flat
2. Soil is clay
3. Stream size to the basin is large
4. Required depth of the irrigation application is large
5. Field preparation is mechanized.

2.2.2 Shape and dimensions of bunds

Bunds are small earth embankments, which contain irrigation water within basins. They are sometimes called ridges, dykes or levees. The irrigation depth and the freeboard determine the height of the bunds. The freeboard is the height above the irrigation depth to be sure that water will not go over the top of the bund.

The width of bunds should be such that leakage will not occur, and that they are stable. **Temporary bunds** are normally 60–120 cm wide at the base and have a height of 15–30 cm above the original ground surface, including a freeboard of 10 cm. Temporary bunds surround fields on which annual crops are grown; these bunds are rebuilt each season (Figure 5). **Permanent bunds** usually have a base width of 130–160 cm and a height of 60–90 cm when constructed (Figure 6). The settled height will be 40–50 cm. This settling (compaction of the soil) will take several months. Permanent bunds are mostly used in rice cultivation, where the same crop is planted on the same fields year after year. The bunds are used as paths in the rice fields as well. Temporary bunds may be used to further subdivide the various fields.

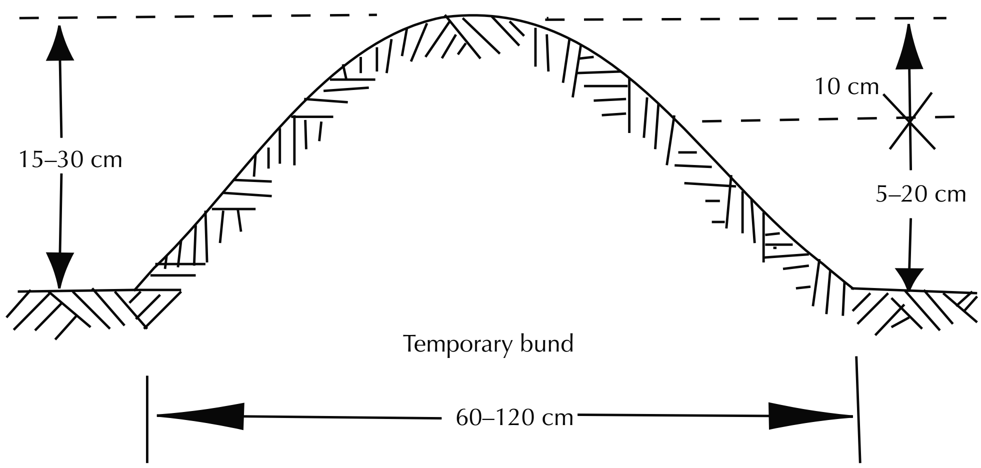

Figure 5. *Shape and dimensions of temporary bunds.*

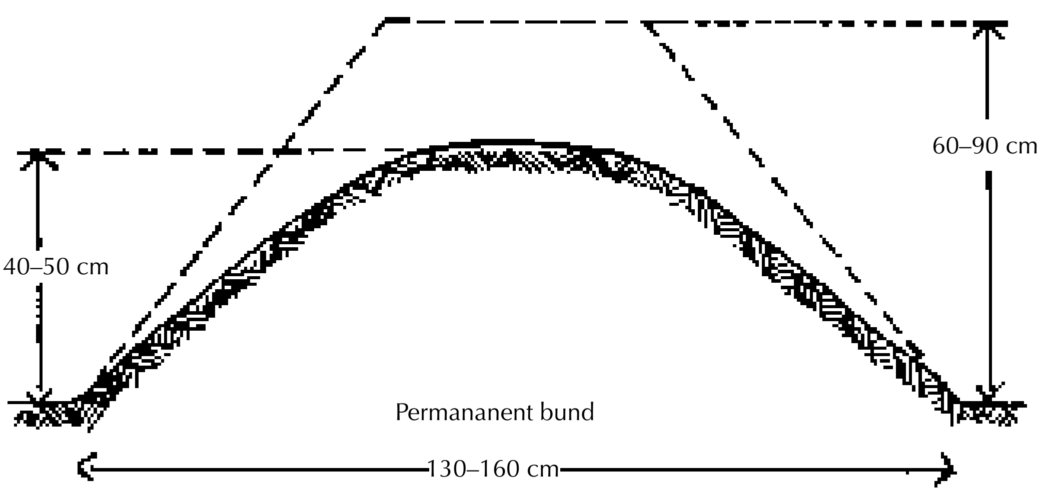

Figure 6 *Shape and dimensions of permanent bunds.*

2.3 Basin construction

The following steps are involved in the construction of basins: setting out; forming the bunds; and smoothing the land within the basins (IWMI 2006).

Step 1: Setting out

Before construction can begin the location of the basins and bunds must be set out on the ground. This can be done using pegs, string lines or chalk powder to mark the lines of the bunds. On flat land, basins may be square or rectangular in shape (Figure 7). Setting out is relatively simple and involves only straight lines. On sloping or undulating land, basins may be irregular in shape and require terracing. Terraces are set out so that the bunds are located along contour lines; the differences in elevation within each basin should not be excessive so that the amount of earth movement required to obtain a level land surface is small (Table 3).

A terrace is set out by first locating a suitable contour line across the land slope (Figure 8). This is the line along which the first bund is constructed. A second line is then set out along a contour further up the slope to mark the location of the next bund.

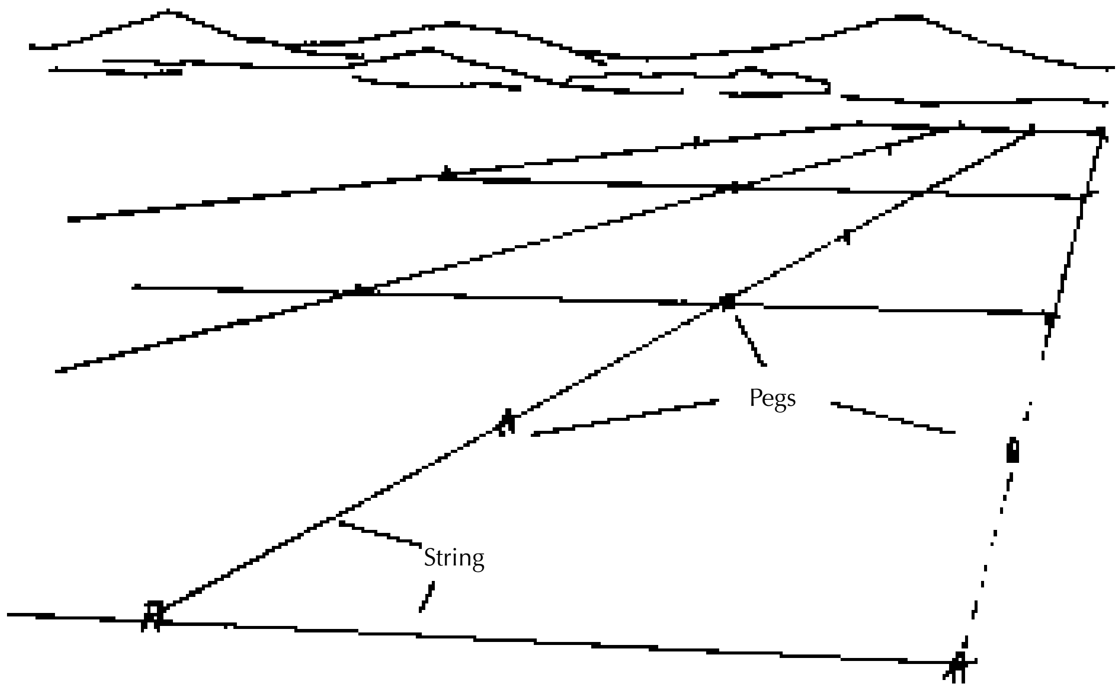

Figure 7. *Setting out the markers.*

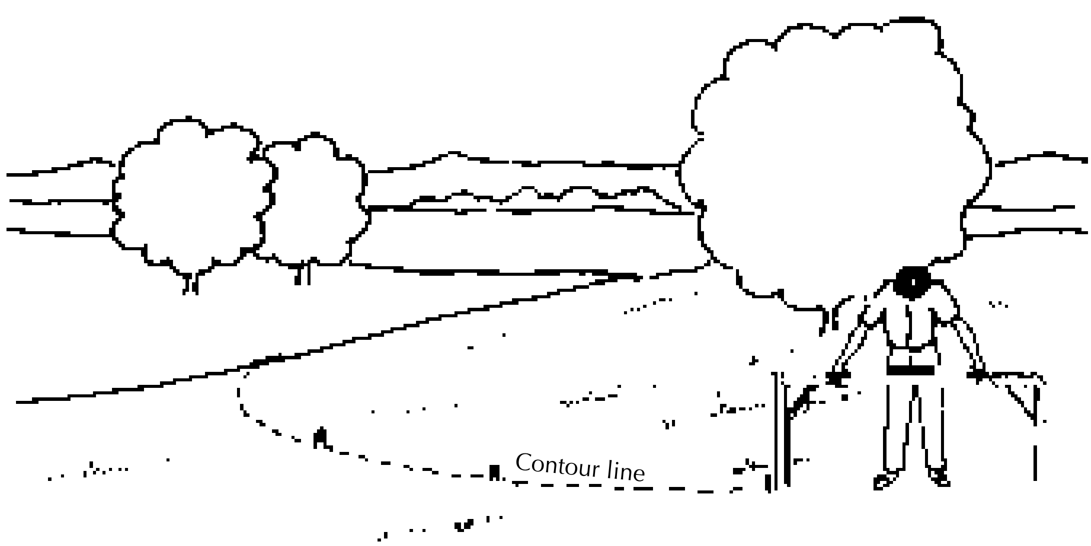

Figure 8. *Marking a contour line.*

Step 2: Forming the bunds

Both temporary and permanent bunds can be formed by hand or by animal or tractor-powered equipment. When soil is gathered from an area close to the bund a 'borrow-furrow' is formed. This furrow can be smoothed out later or be used as a farm channel or drain. When forming bunds for terraces, soil should only be taken from the uphill side of the bund. A useful piece of equipment for forming bunds is an A-frame (Figure 9). This consists of two boards set on edge and cross-braced, with a wide opening at the front and a narrow opening at the rear. The boards act as blades for cutting into the soil and forming it into a ridge or bund (Figure 10). A typical A-frame that is suitable to be drawn by animals has blades 20 cm deep and 2 m long spaced 1.5 m apart at the front and 30 cm apart at the rear.

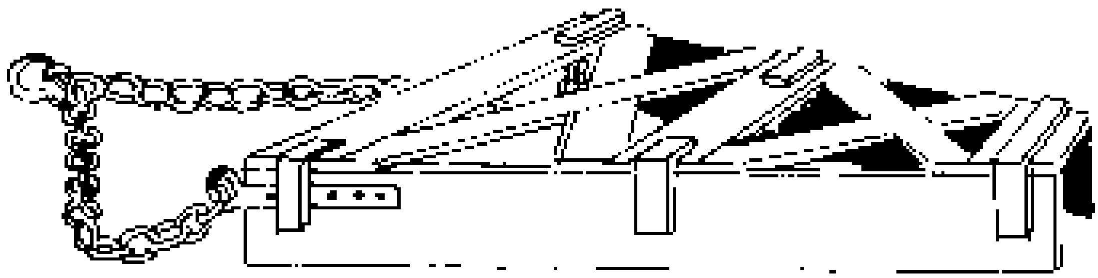

Figure 9. *Wooden A-frame.*

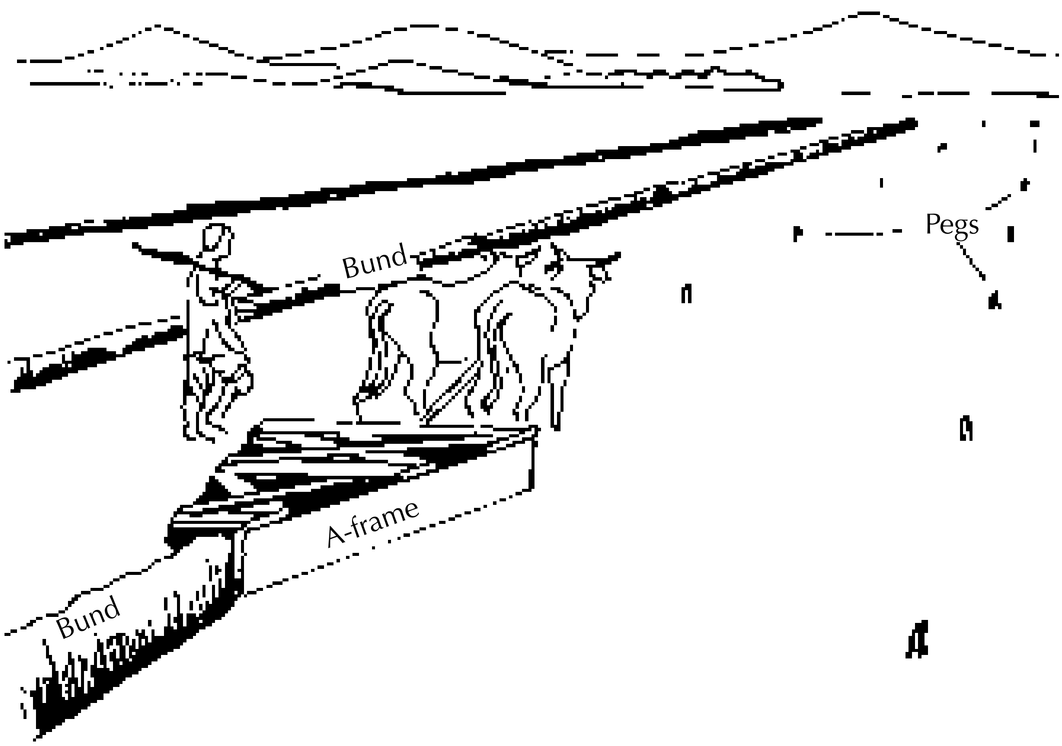

Figure 10. *Making of bunds.*

Before forming bunds with an A-frame it is useful to loosen the top-soil to a depth of 10–15 cm so that the blades can easily collect sufficient soil.

Whichever method is used it is important that the bunds are properly compacted so that leakage cannot occur.

Step 3: Smoothing the land

This can be the most difficult part of basin construction and involves very careful levelling of the land within each basin. On flat land this involves smoothing out the minor high and low spots so that the difference in level is less than 3 cm. This can be done by hand or by a tractor-drawn land plane depending on the size of the basin. However, a 3 cm level difference is almost impossible to judge by eye and only when applying water will it become obvious where high and low spots still exist. Thus several attempts may be required to correct the levelling. Levelling rice basins can be much simpler. These are first cultivated and then filled with water. As the water surface is level, it will be easy to locate the high spots. These can be smoothed down and the water in the basin gradually lowered to reveal other high areas. The smoothing is usually done by an animal or tractor-drawn float. This method of smoothing usually destroys the soil structure. This is not a problem when growing rice, but it is not a recommended procedure for other crops. On sloping land, where terraces are constructed, levelling is achieved by moving soil from the upper part of the slope to the lower part. Care is needed when filling in the borrow furrow to ensure that the bund height is maintained so that over flowing is avoided.

2.4. Irrigating basins

There are two methods to supply irrigation water to basins: the direct method and the cascade method.

The direct method for supplying irrigation water to basin involves the irrigation water being led directly from the field channel into the basin through siphons or bund breaks. Figure 11 shows that 'Basin a' is irrigated first, then 'Basin b' is irrigated and so on. This method can be used for most crop types and is suitable for most soils. On sloping land, where terraces are used, the irrigation water is supplied to the highest terrace, and then allowed to flow to a lower terrace and so on. Figure 12 shows the cascade method for supplying irrigation water to basins showing that the water is supplied to the highest terrace (a.1) and is allowed to flow through terrace a.2 until the lowest terrace (a.3) is filled. The intake of terrace a.1 is then closed and the irrigation water is diverted to terrace b.1 until b.1, b.2 and b.3 are filled, and so on. This is a good method to use for paddy rice on clay soils where percolation and seepage losses are low. However, for other crops on sandy or loamy soils, percolation losses can be excessive while water is flowing through the upper terraces to irrigate the lower ones. This problem can be overcome by using the borrow-furrow as a small channel to take water to the lower terrace. The lower terrace is irrigated first and when complete the bund is closed and water is diverted into the next terrace. Thus the terrace nearest the supply channel is the last to be irrigated.

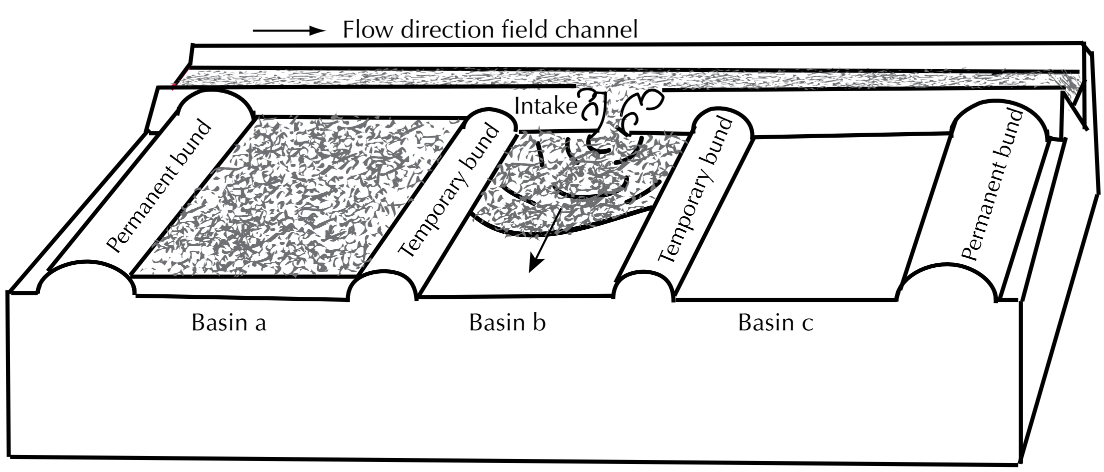

Figure 11. *The direct method.*

When long cascades are used for growing rice it is common practice to allow water to flow continuously into the terraces at low discharge rates. The water demand in the cascade can easily be monitored by observing the drainage flow. If there is no drainage then more water may be required at the top of the cascade. If there is a drainage flow then it is possible to reduce the inflow.

2.4.1 Wetting patterns

For good crop growth it is very important that the right quantity of water is supplied to the root zone and that the root zone is wetted uniformly.

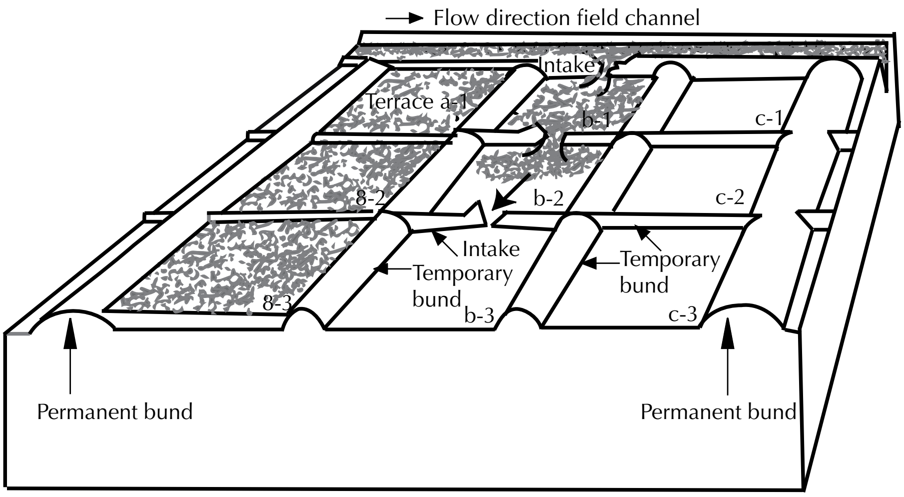

Figure 12. *The cascade method.*

If crops receive too little water, they will suffer from drought stress, and yield will be reduced. If they receive too much water, then water is lost through deep percolation and, especially on clay soils, permanent pools may form, causing the plants to drown. The amount of irrigation water that should be supplied to the root zone—in other words 'the net irrigation depth'—is discussed in the previous chapter. How the irrigation water can be evenly distributed in the root zone is explained below.

Ideal wetting pattern

To obtain a uniformly wetted root zone, the surface of the basin must be level and the irrigation water must be applied quickly. Figure 13 shows an ideal wetting pattern: the basin is level and the right quantity of water has been supplied with the correct stream size. As can be seen from Figure 13, it is not possible to have the wetting pattern and root zone coincide completely. The part of the basin near the field channel is always in contact with the irrigation water longer than the opposite side of the basin. Therefore percolation losses will occur near the field channel, if sufficient water is supplied to the opposite side of the basin.

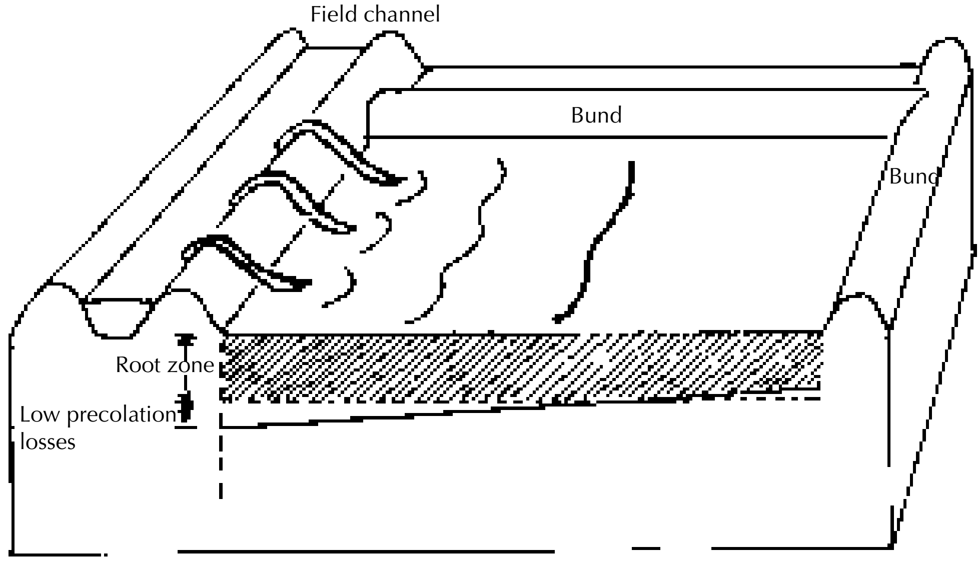

Figure 13. *Ideal wetting pattern.*

Poor wetting patterns

Poor wetting patterns can be caused by:

- Unfavourable natural conditions, e.g. a compacted subsoil layer, or different soil types within one basin;
- Poor layout, e.g. a poorly levelled surface;
- Poor management, e.g. supplying incorrect stream size, applying too little or too much water.

i. Unfavourable natural conditions

A compacted subsoil layer can sometimes occur in a basin some 30–50 cm below the soil surface. Infiltration through this layer may be very slow and so water tends to accumulate above this layer: a 'perched' water table is formed (Figure 14). This may result in water logging. This situation may be very helpful for growing rice but will be harmful for other crops. The compacted layer can be removed by using deep ploughs or rippers, which break up the subsoil. Different soil types within a basin can cause uneven water distribution. This problem can be solved by re-aligning basin boundaries so that each basin contains only one soil type.

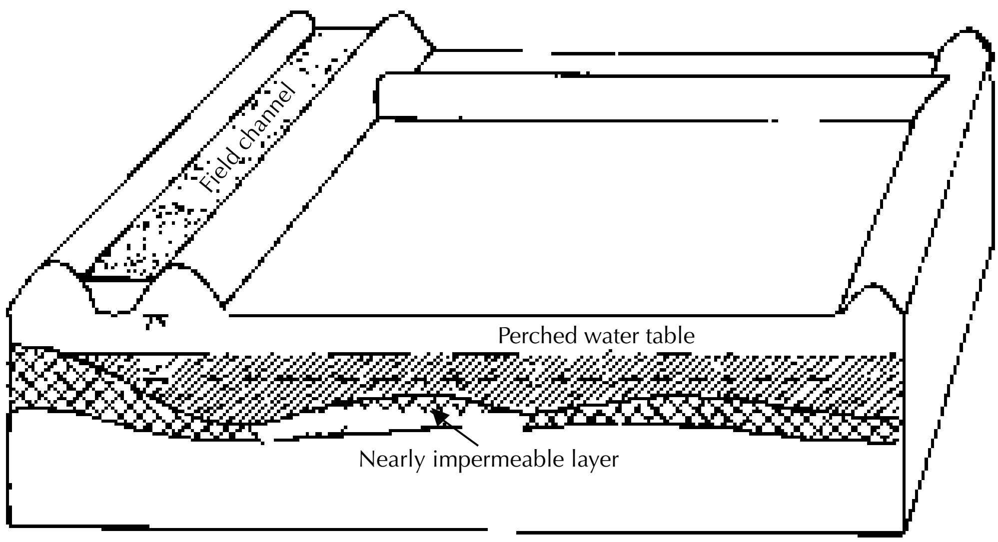

Figure 14. *A nearly impermeable layer above which a perched water table is formed.*

ii. Poor layout

Figure 15 shows what happens to the wetting pattern if the soil surface is not level. Some parts of the root zone receive too little water and in the lower parts water may pond or be lost through deep percolation. Plants suffer in the drier parts because they receive too little water and wilt. Plants may also suffer in the wet parts as plant nutrients are carried away from the root zone to the subsoil and, especially on clay soils, the plants may drown. These faults can easily be corrected by careful land levelling.

iii. Poor management

Figure 16 shows what happens if the basin is irrigated too slowly, by using a stream size which is too small. The part of the basin that receives irrigation water first and for the longest time (near the supply channel) receives too much water. Percolation losses occur, nutrients are washed away and the plants may drown. The other end of the basin remains too dry. The plants there do not receive enough water and wilt. The solution to the problem is to:

- increase the stream size so that the basin will be flooded more rapidly, or
- subdivide the basin into smaller basins; smaller basins need a smaller stream size than larger basins.

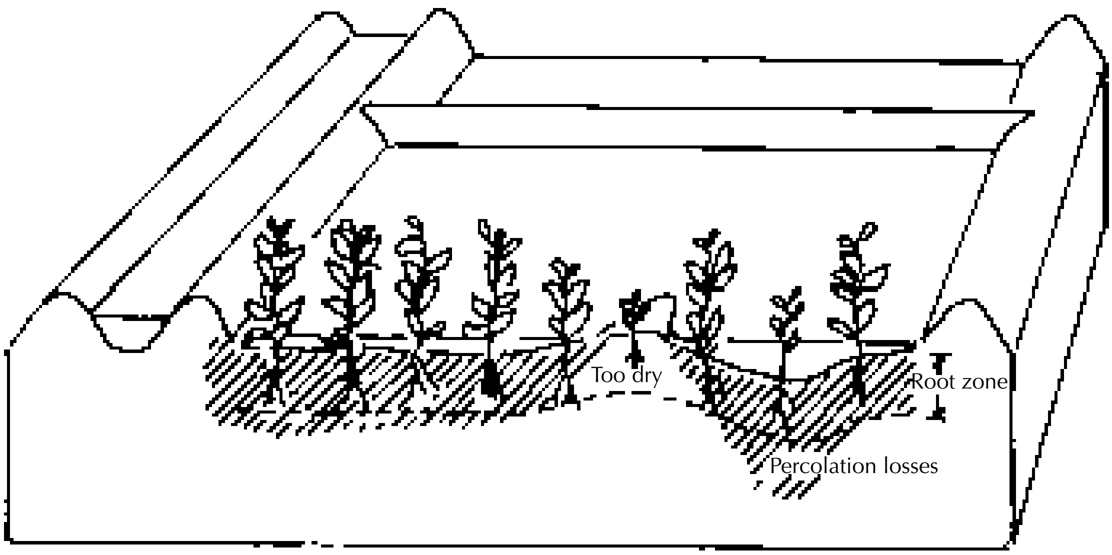

Figure 15. *Wetting pattern of a poorly levelled basin.*

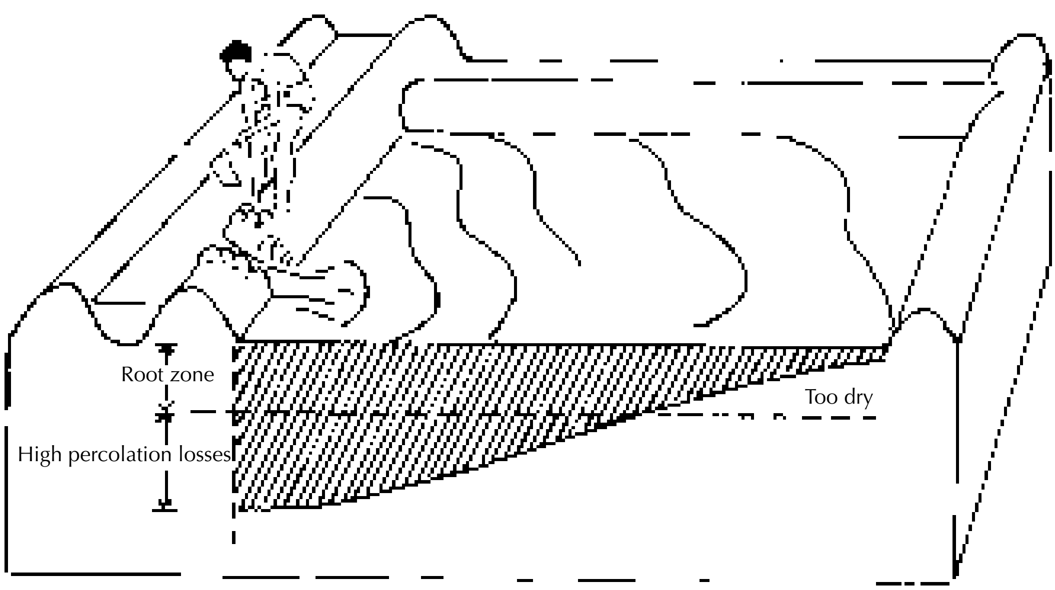

Figure 16. *Wetting pattern when the flow rate is insufficient.*

Figure 17 shows what happens if insufficient water is applied to fill the root zone. This is called 'under-irrigation' and is caused by under-estimating the time needed to fill the root zone. There are no percolation losses during under-irrigation. Although water may be used efficiently by this approach, frequent irrigation will be necessary to meet crop water needs. Continual under-irrigation will eventually restrict root development and the crop may suffer when there are delays in irrigating, e.g. when water is in short supply or the supply system breaks down.

Figure 18 shows what happens if too much water is supplied to a basin. This is called 'over-irrigation'. The percolation losses are high, the plant nutrients are washed away and, on clay soils, the plants may even drown. The obvious solution is to apply less water.

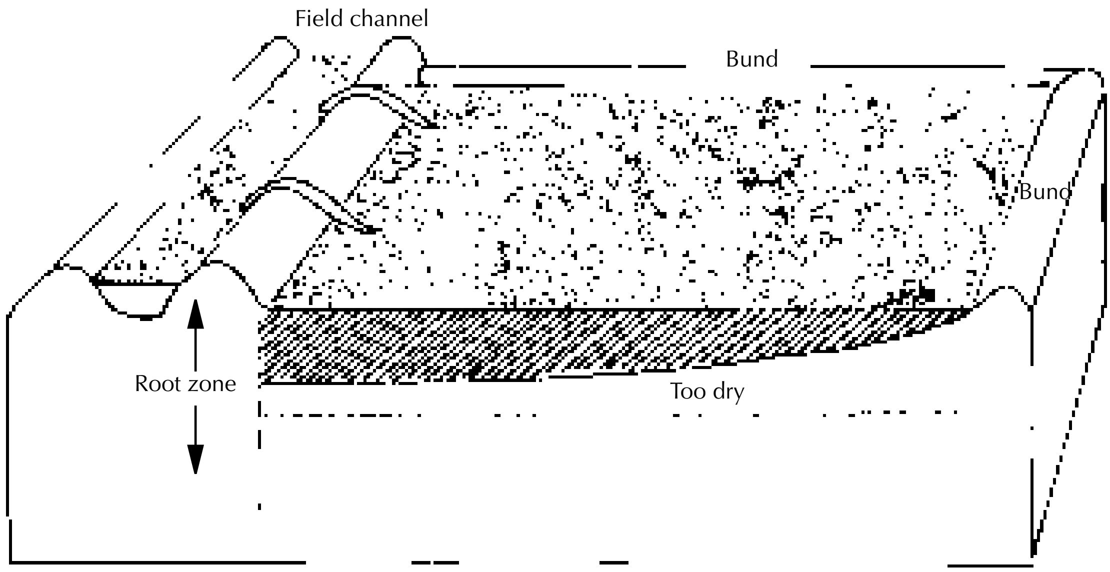

Figure 17. *Under-irrigation.*

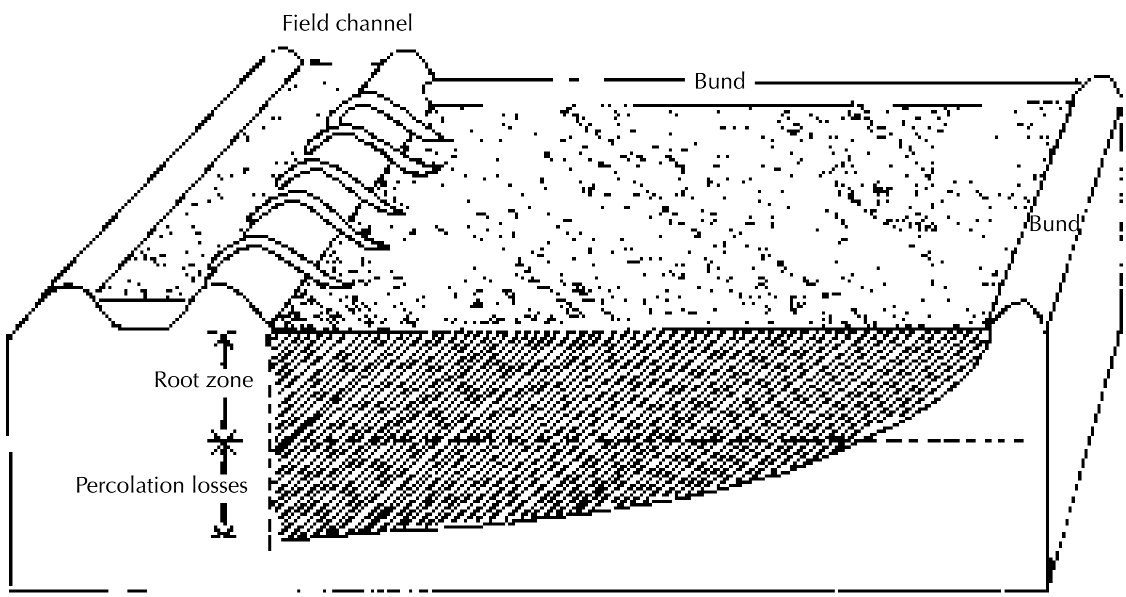

Figure 18. *Over-irrigation.*

2.5 Maintenance of basins

Bunds are susceptible to erosion, which may be caused by rainfall, flooding or the passing of people when being used as footpaths. Rats may also dig holes in the sides of the bunds. It is therefore important to check the bunds regularly, notice defects and repair them instantly, before greater damage is done. Before each growing season, the basins should be checked to see that they remain level. During pre-irrigation it can easily be seen where higher and lower spots are; these should be smoothed out. Also, the field channels should be kept free from weeds and silt deposits.

Chapter 3 Furrow irrigation

Chapter objectives:

At the end of this chapter, you will be able to:

- identify when to use furrow irrigation
- design furrows
- layout furrows
- construct furrows
- understand different planting techniques in furrows
- irrigate furrows
- maintain furrows

Furrows are small, parallel channels that are made to carry water in order to irrigate the crops (Hansen et al. 1980; Garg 1989; Shah et al. 2002; IWMI 2006). The crops are usually grown on the ridges between the furrows (Figure 19).

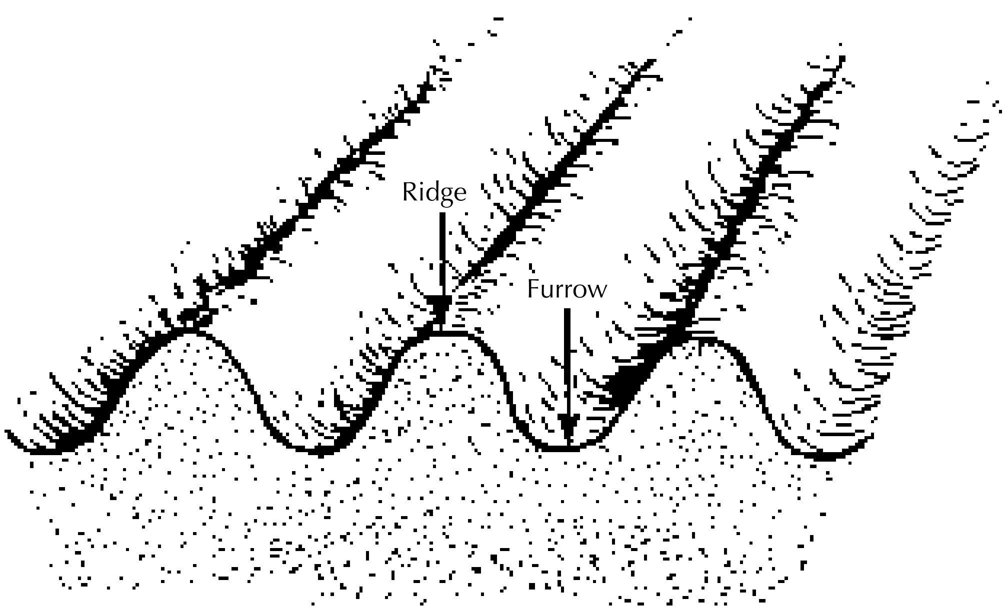

Figure 19. *Top view and cross-section of furrows and ridges.*

3.1 When to use furrow irrigation

Furrow irrigation is suitable for a wide range of crops, slopes and soil types. Furrow irrigation is suitable for many crops, especially row crops (Reddy and Reddy 1995; Shah et al. 2002; Namara et al. 2005; IWMI 2006; Mloza-Banda 2006). Crops those can be damaged, if water covers their stem or crown, should be irrigated by furrows. Furrow irrigation is also suited to the growing of tree crops. In the early stages of tree planting, one furrow alongside the tree row may be sufficient but as the trees develop then two or more furrows can be constructed to provide sufficient water. Sometimes a special zigzag system is used to improve the spread of water (Figures 20a and b). Corrugation irrigation, frequently mentioned in literature, is a special type of furrow irrigation, used for broadcast crops. Corrugations are small hills pressed into the soil surface. The application of this method is limited and is not included in this manual. In summary, the following crops can be irrigated by furrow irrigation:

- row crops such as maize, sunflower, sugarcane, soybean;
- crops that would be damaged by inundation, such as tomatoes, vegetables, potatoes, beans;
- fruit trees such as citrus, grape;
- broadcast crops (corrugation method) such as wheat.

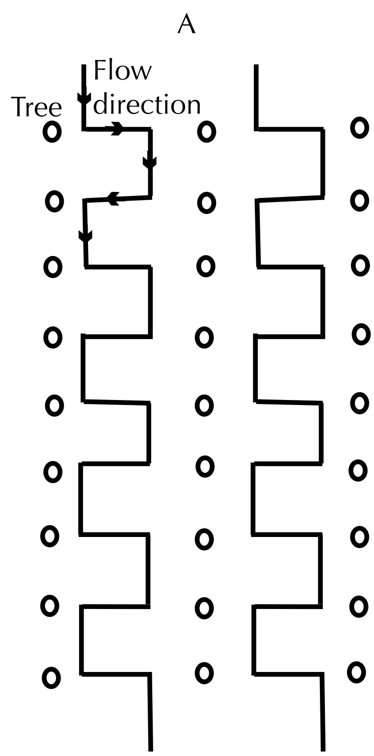

Figure 20a. *Zigzag furrows used for irrigating trees on land with a moderate slope (0.5–1.5%).*

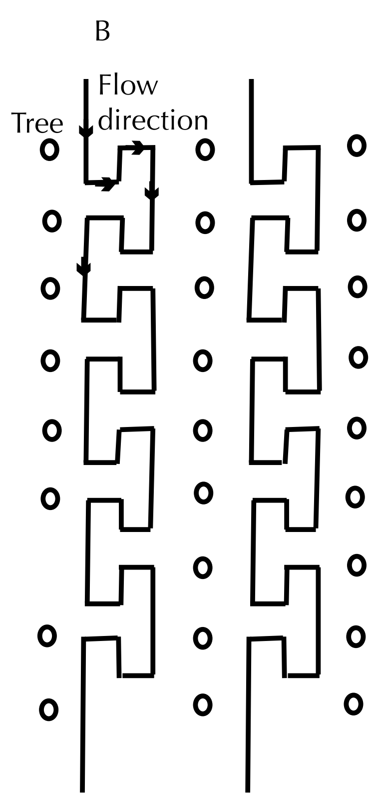

Figure 20b. *Zigzag furrows irrigating on fairly flat slopes (under 0.5%).*

Uniform flat or gentle slopes are preferred for furrow irrigation. These should not exceed 0.5%. Usually a gentle furrow slope is provided up to 0.05% to assist drainage following irrigation or excessive rainfall with high intensity.

On undulating land furrows should follow the land contours. However, this can be a difficult operation requiring very careful setting out of the contours before cutting the furrows.

Furrows can be used on most soil types. However, as with all surface irrigation methods, very coarse sands are not recommended, as percolation losses can be high. Soils that crust easily are especially suited to furrow irrigation because the water does not flow over the ridge, and so the soil in which the plants grow remains friable.

3.2 Furrow layout

This section deals with the shape, length and spacing of furrows. Generally, the shape, length and spacing are determined by natural circumstances, i.e. slope, soil type and available stream size. However, other factors may influence the design of a furrow system, such as the irrigation depth, farming practice and the field length.

3.2.1 Furrow length

Furrows must fit with the slope, the soil type, the stream size, the irrigation depth, the cultivation practice and the field length. The impact of these factors on the furrow length is discussed below.

Slope

Although furrows can be longer when the land slope is steeper, the maximum recommended furrow slope is 0.5% to avoid soil erosion. Furrows can also be level and are thus very similar to long narrow basins. However, a minimum grade of 0.05% is recommended so that effective drainage can occur following irrigation or excessive rainfall. If the land slope is steeper than 0.5%, then furrows can be set at an angle to the main slope or even along the contour to keep furrow slopes within the recommended limits. Furrows can be set in this way when the main land slope does not exceed 3%. Beyond this there is a major risk of soil erosion following a breach in the furrow system. On steep land, terraces can also be constructed (see Chapter 2 on basin irrigation) and furrows cultivated along the terraces.

Soil type

In sandy soils water infiltrates rapidly. Furrows should be short (less than 110 m), so that water will reach the downstream end without excessive percolation losses. In clay soils, the infiltration rate is much lower than in sandy soils. Furrows can be much longer on clayey soils than on sandy soils.

Stream size

Normally stream sizes up to 0.5 litre/sec will provide an adequate irrigation provided the furrows are not too long. When larger stream sizes are available, water will move rapidly down the furrows and so generally furrows can be longer. The maximum stream size that will not cause erosion will depend on the furrow slope. It is advised not to use stream sizes larger than 3.0 litres/sec.

Irrigation depth

Applying larger irrigation depths usually means that furrows can be longer as there is more time available for water to flow down the furrows and infiltrate.

Cultivation practice

When farming is mechanized, furrows should be made as long as possible to facilitate the work. Short furrows require a lot of attention, as the flow must be changed frequently from one furrow to the next. However, short furrows can usually be irrigated more efficiently than long ones, as it is much easier to keep the percolation losses low.

Field length

It may be practical to make the furrow length equal to the length of the field, instead of the ideal length, when this would result in a small piece of land left over (Figure 21). Equally the length of field may be much less than the maximum furrow length. This is not usually a problem and furrow lengths are made to fit the field boundaries.

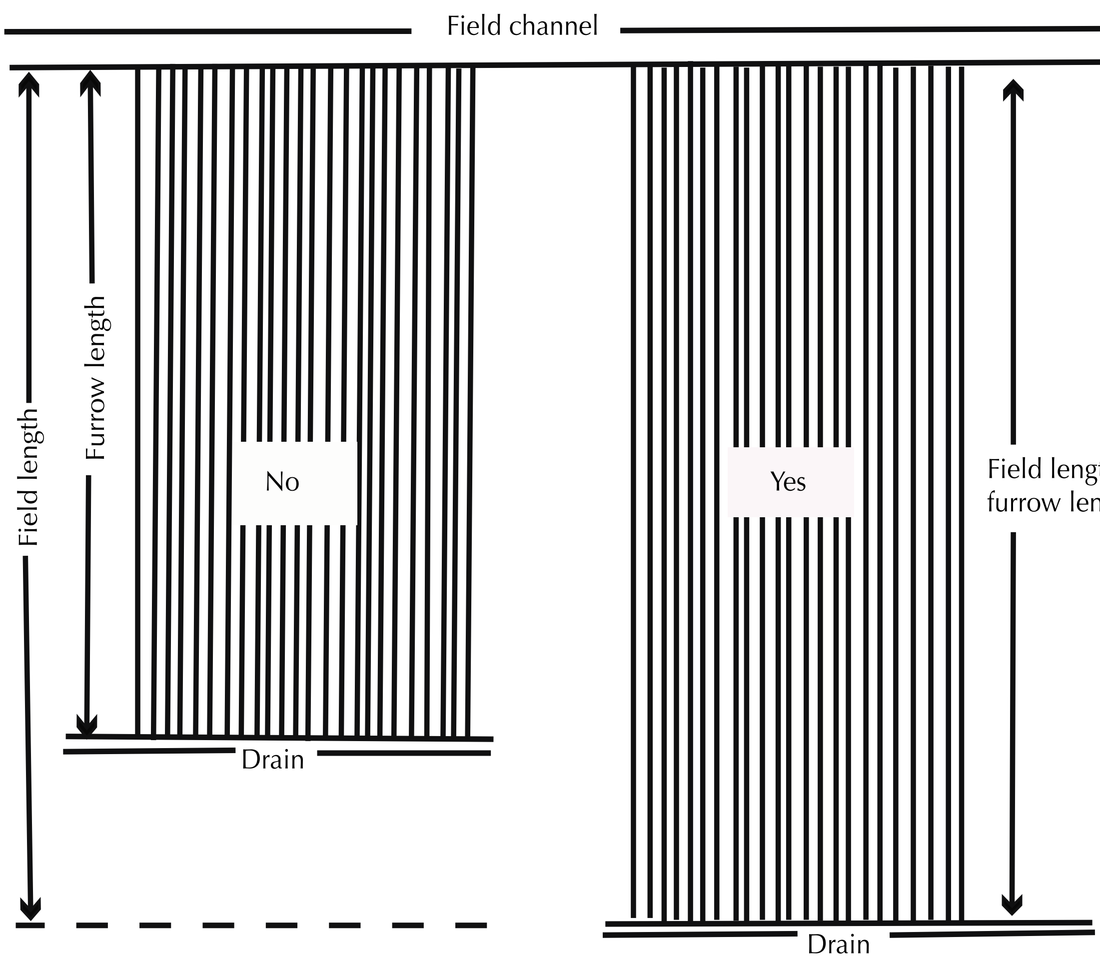

Figure 21. *Field length and furrow length.*

Table 5 gives some practical values of maximum furrow lengths under small-scale irrigation conditions. The values shown in Table 5 are lower than those generally given in irrigation handbooks. These higher values are appropriate under larger scale, fully mechanized conditions.

Table 5. *Practical values of maximum furrow lengths (m) depending on slope, soil type, stream size and net irrigation depth*

Furrow slope (%)	Maximum stream size (litres/sec per furrow)	Clay		Loam		Sand	
		Net irrigation depth (mm)					
		50	75	50	75	50	75
0.0	3.0	100	150	60	90	30	45
0.1	3.0	120	170	90	125	45	60
0.2	2.5	130	180	110	150	60	95
0.3	2.0	150	200	130	170	75	110
0.5	1.2	150	200	130	170	75	110

Important:

This table only provides approximate information relating furrow slope, soil type, stream size and irrigation depth to furrow lengths. This should only be used as a guide as the data is based primarily on field experience and not on any scientific relationships. Maximum values of furrow length are given for reasonably efficient irrigation. However, furrow lengths can be even shorter than those given in the table and in general this will help to improve irrigation efficiency. An appropriate system can be developed for a given locality by installing a furrow system, following the guidelines, and then evaluating its performance.

3.2.2 Furrow shape

The soil type and the stream size influence the shape of the furrows.

Soil type

In sandy soils, water moves faster vertically than sideways (lateral). Narrow, deep V-shaped furrows are desirable to reduce the soil area through which water percolates (Figure 22). However, sandy soils are less stable, and tend to collapse, which may reduce the irrigation efficiency.

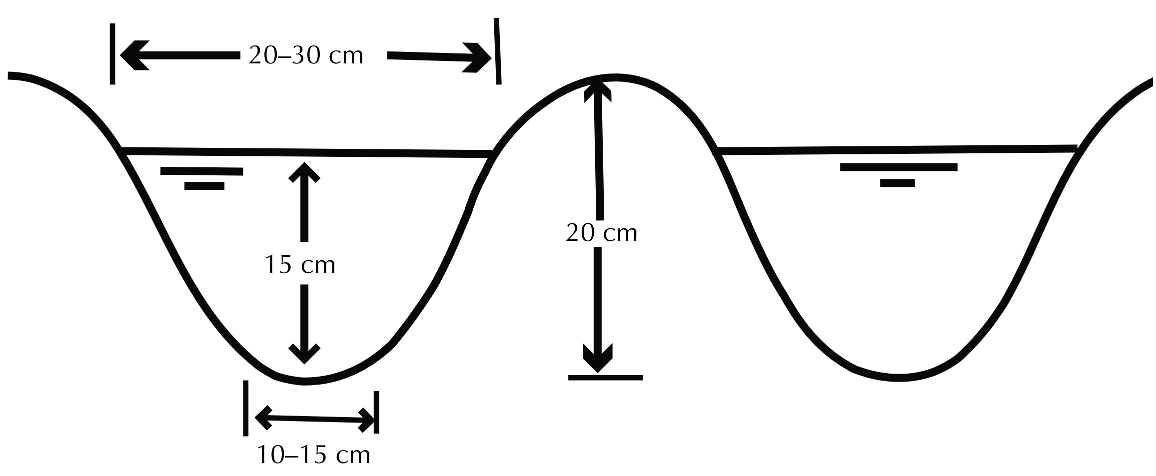

Figure 22. *A deep and narrow furrow on a sandy soil.*

In clay soils, there is much more lateral movement of water and the infiltration rate is much less than for sandy soils. Thus a wide, shallow furrow is desirable to obtain a large wetted area (Figure 23) to encourage infiltration.

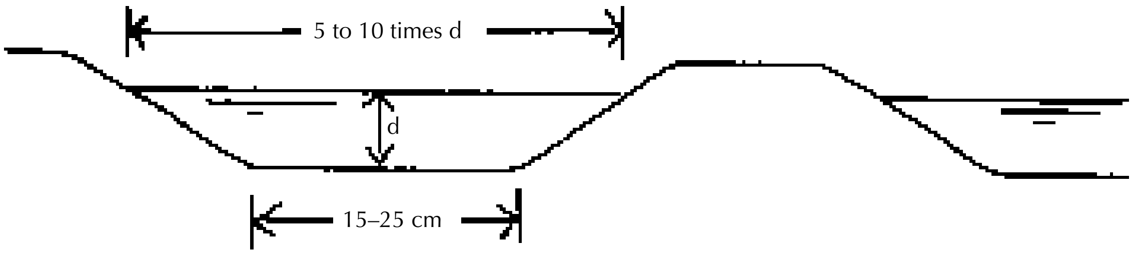

Figure 23. *A wide and shallow furrow on a clay soil.*

Stream size: In general, the larger the stream size the larger the furrow must be to contain the flow.

3.2.3 Furrow spacing

The spacing of furrows is influenced by the soil type and the cultivation practice.

Soil type

As a rule, for sandy soils the spacing should be between 30 and 60 cm, i.e. 30 cm for coarse sand and 60 cm for fine sand.

In clay soils, the spacing between two adjacent furrows should be 75–150 cm. In clay soils, double-ridged furrows—sometimes called beds—can also be used. Their advantage is that more plant rows are possible on each ridge, facilitating manual weeding. The ridge can be slightly rounded at the top to drain off water that would otherwise tend to pond on the ridge surface during heavy rainfall (Figure 24).

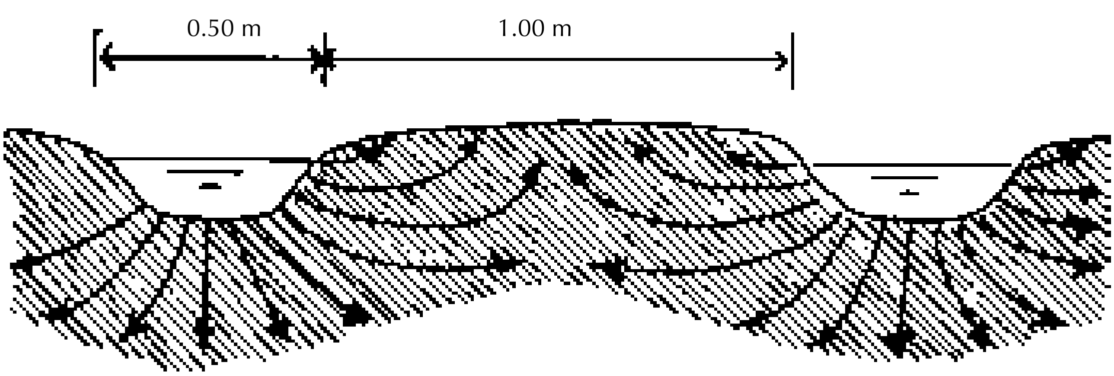

Figure 24. *A double-ridged furrow.*

Cultivation practice

In mechanized farming a compromise is required between the machinery available to cut furrows and the ideal spacing for crops. Mechanical equipment will result in less work if a standard width between the furrows is maintained, even when the crops grown normally require a different planting distance. This way the spacing of the tool attachment does not need to be changed when the equipment is moved from one crop to another. However, care is needed to ensure that the standard spacing provide adequate lateral wetting on all soil types.

3.3 Furrow construction

The most common way to construct furrows is with a rigger. Figures 25 and 26 show animal- and hand-drawn riggers.

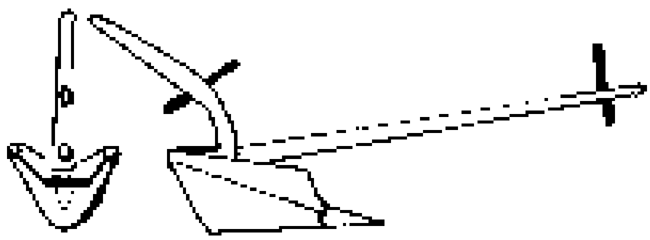

Figure 25. *Ridger plough: wooden body, animal-drawn.*

Figure 26. *Ridger plough: iron type, animal-drawn.*

3.3.1 Construction of furrows on flat or gentle slope

The following steps are taken to construct furrows: setting out; forming one (or more) ridge(s); forming one (or more) parallel ridge(s).

Step 1

A straight line is set out in the field along the proposed line of furrows. This can be done by setting up ranging poles or marking a line on the ground with chalk powder or small mounds of earth. An experienced ploughman should be able to plough along the line by aligning the poles or earth mounds by eye (Figure 27).

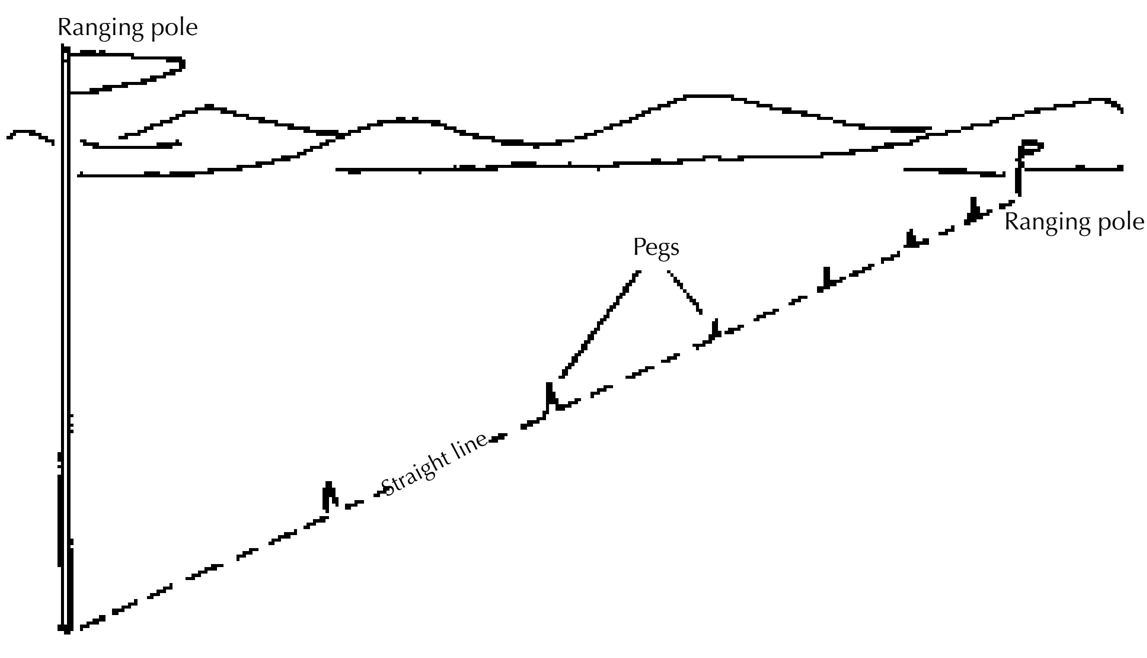

Figure 27. *Markers are put along a straight line.*

Step 2

The ridger is moved along the line. The resulting furrow should be straight. If not, the area should be ploughed again and the procedure repeated.

Step 3

About every five (5) metres, a new straight line should be set out. If a ridger-drawbar connected with a tractor is used, four furrows can be drawn simultaneously. On the track back the left ridger is put in the last furrow track to make sure the new furrows arc parallel to the previous ones. Here it should be checked that straight lines are followed: for every track a centre line is set out.

Attention: It should always be kept in mind that a new straight line has to be set out before a new furrow track is made.

3.4 Irrigating furrows

Water is supplied to each furrow from the field canal, using siphons or spiles. Sometimes, instead of supplying the field canal with siphons or spiles, a gated pipe is used. Depending on the available flow in the farm channel, several furrows can be irrigated at the same time. Runoff at the ends of furrows can be a problem on sloping land. This can be as much as 30% of the inflow, even under good conditions. Therefore a shallow **drain** should always be made at the end of the field to remove excess water. When no drain is made, plants may be damaged by waterlogging. Light vegetation allowed to grow in the drain can prevent erosion. Excessive runoff can be prevented by reducing the inflow once the irrigation water has reached the end of the furrows (Davis 1961; Stringham and Keller 1979; Humphreys 1987; Taffa 2004). This is called **cut-back** irrigation. It may also be possible to reuse runoff water further down the farm.

3.4.1 Wetting patterns

In order to obtain a uniformly wetted root zone, furrows should be properly spaced, have a uniform slope and the irrigation water should be applied rapidly. As the root zone in the ridge must be wetted from the furrows, the downward movement of water in the soil is less important than the lateral (or sideways) water movement. Both lateral and downward movement of water depends on soil type as can be seen in Figure 28 (a, b, c).

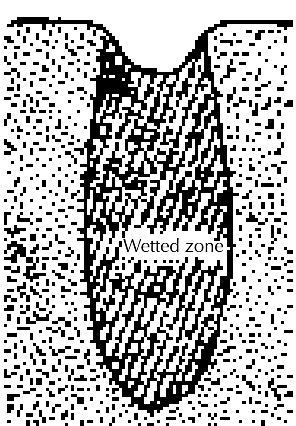

Figure 28a. *Different wetting patterns in furrows, depending on the soil type (sand).*

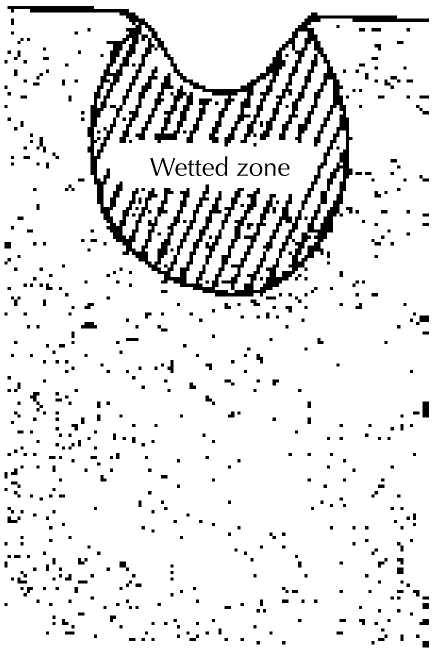

Figure 28b. *Different wetting patterns in furrows, depending on the soil type (loam).*

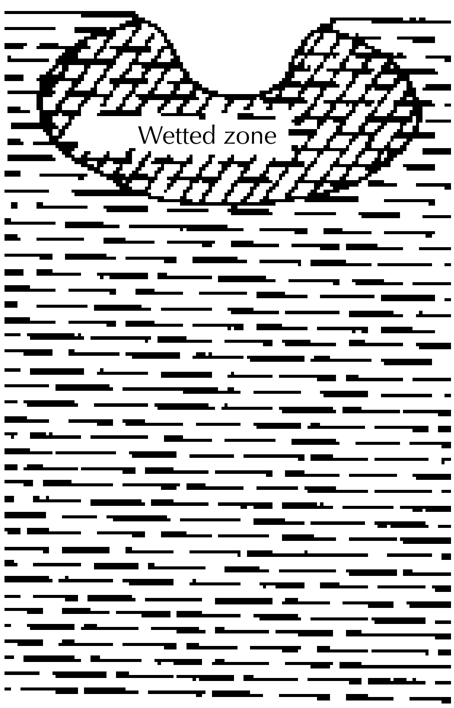

Figure 28c. *Different wetting patterns in furrows, depending on the soil type (clay).*

Ideal wetting pattern

In an ideal situation adjacent wetting patterns overlap each other, and there is an upward movement of water (capillary rise) that wets the entire ridge (see Figure 29), thus supplying the root zone with water.

To obtain a uniform water distribution along the furrow length, it is very important to have a uniform slope and a large enough stream size so that water advances rapidly down the furrow. In this way large percolation losses at the head of the furrow can be avoided.

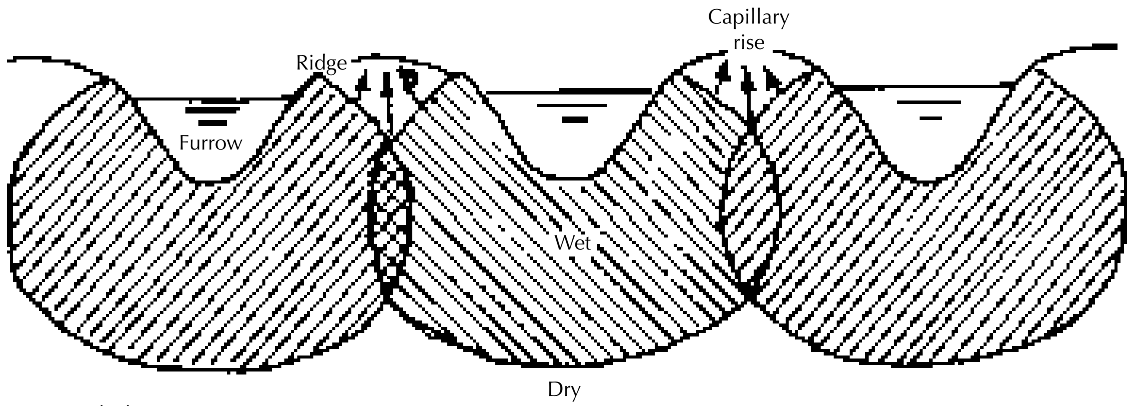

Figure 29. *Ideal wetting pattern.*

Poor wetting patterns

Poor wetting patterns can be caused by:

- Unfavourable natural conditions, e.g. a compacted layer, different soil types, uneven slope;
- Poor layout, e.g. a furrow spacing too wide;
- Poor management: supplying a stream size that is too large or too small, stopping the inflow too soon.

i. Unfavourable natural conditions

Compacted soil layers or different soil types have the same effect on furrow irrigation as they have on basin irrigation. The solution to the problem is also similar. An uneven slope can result in uneven wetting along the furrow. Water flows fast down the steep slopes and slowly down the flatter slopes. This affects the time available for infiltration and results in poor water distribution. The problem can be overcome by changing the land to a uniform slope.

ii. Poor layout

If the furrow spacing is too wide (Figure 30) then the root zone will not be adequately wetted. The spacing of furrows needs careful selection to ensure the adequate wetting of the entire root zone (Figure 30).

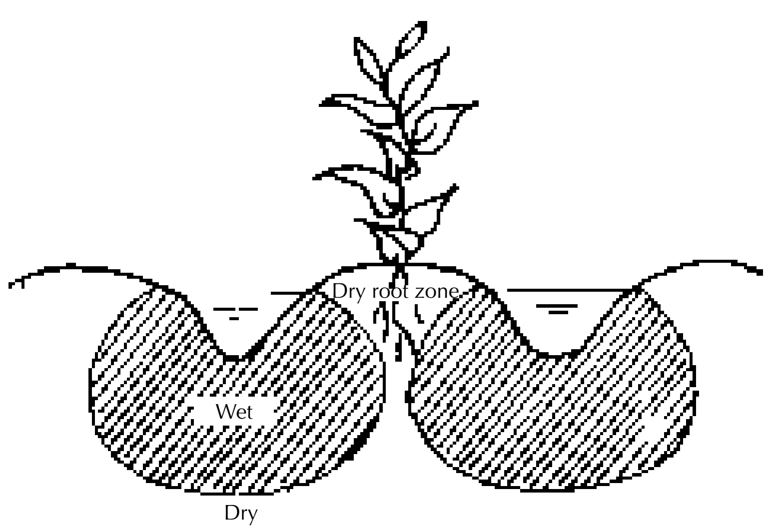

Figure 30. *The spacing between two adjacent furrows is too wide.*

iii. Poor management

A stream size that is too small (Figure 31) will result in inadequate wetting of the ridges. Even if the plants are located at the sides of the ridge, not enough water will be available. A small stream size will also result in poor water distribution along the length of the furrow. The advance will be slow and too much water will be lost through deep percolation at the head of the furrow.

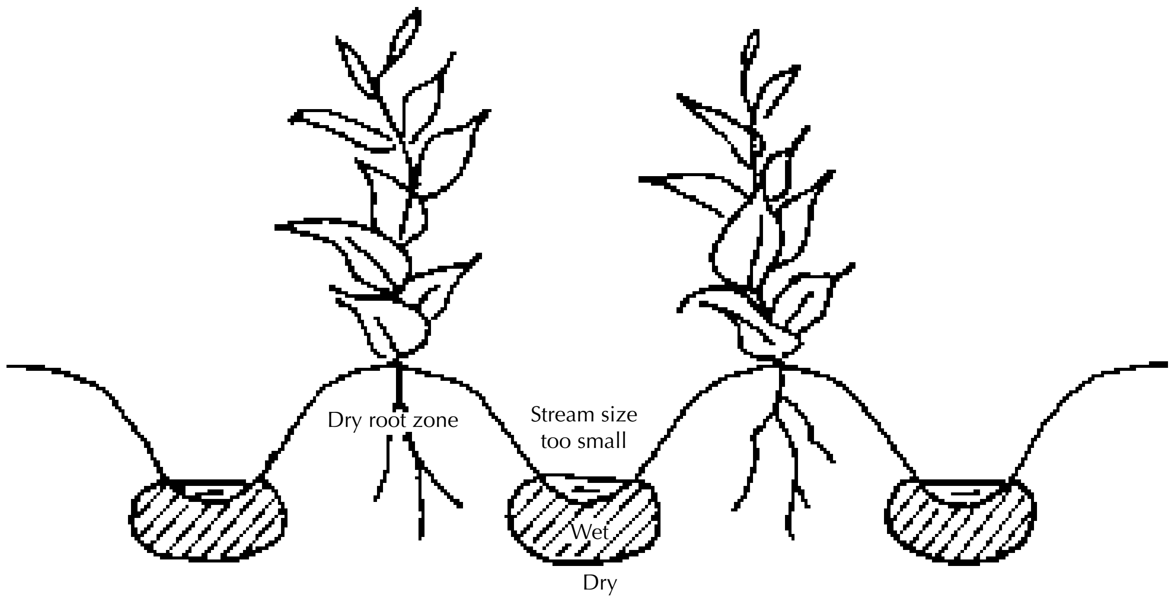

Figure 31. *Stream size is too small to wet the ridge.*

If the stream size is too large on flat slopes, overtopping of the ridge may occur (Figure 32). On steeper slopes with too large a stream size, erosion of the bed and sides of the furrow may take place (Figure 32).

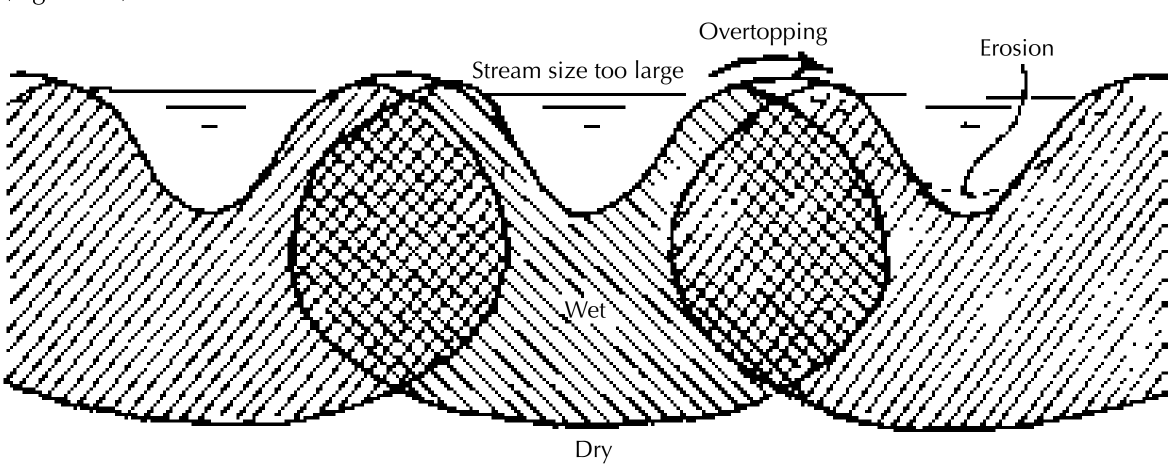

Figure 32. *Stream size too large causing overtopping or erosion.*

A common management fault is to stop the inflow too soon. This is usually done to reduce runoff, but it results in a poor water distribution and the plants in particular at the end of the furrow do not get enough water. If the inflow of irrigation water is not stopped soon enough, the runoff is excessive and plants at the end of the furrow may drown when an adequate drainage system to evacuate excess water is not provided.

3.5 Planting techniques

The location of plants in a furrow system is not fixed but depends on the natural circumstances. A few examples will be mentioned.

- In areas with heavy rainfall, the plants should stand on top of the ridge in order to prevent damage as a result of water logging (Figure 33).
- If water is scarce, the plants may be put in the furrow itself, to benefit more from the limited water (Figure 34).
- As salts tend to accumulate in the highest point, a crop on saline soils should be planted away from the top of the ridge. Usually it is planted in two rows at the sides (Figure 35). However, it is important to make sure there is no danger of water logging.

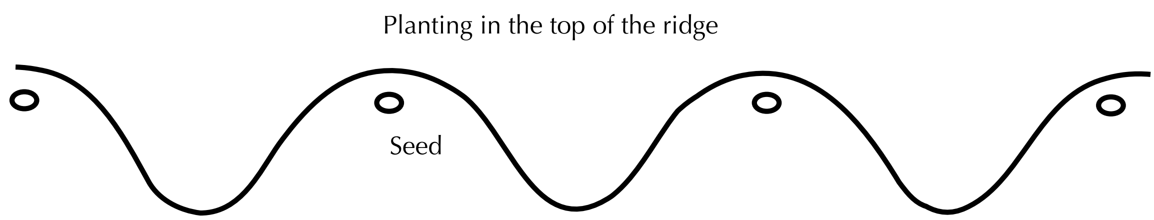

Figure 33. *Protection against water logging.*

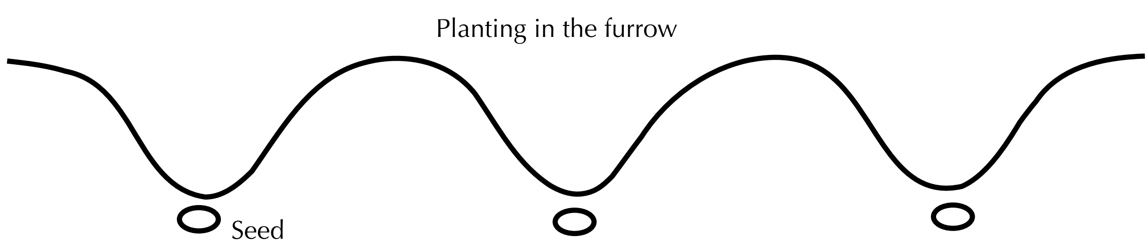

Figure 34. *Protection against water scarcity.*

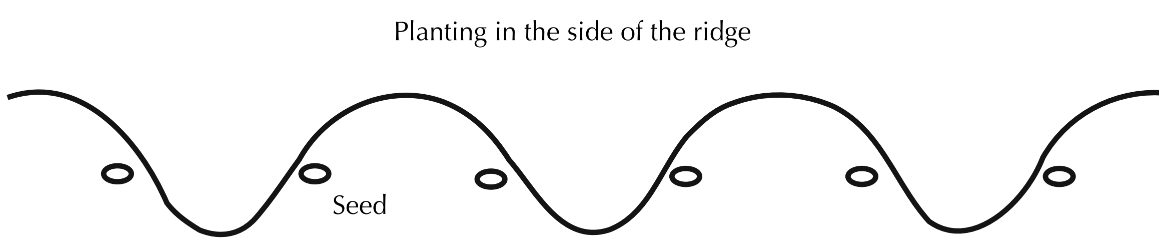

Figure 35. *Protection against accumulation of salt.*

3.6 Maintenance of furrows

After construction, the furrow system should be maintained regularly; during irrigation it should be checked if water reaches the downstream end of all furrows. There should be no dry spots or places where water stays ponding. Overflowing of ridges should not occur. The field channels and drains should be kept free from weeds.

Chapter 4 Other methods of surface irrigation

Chapter objectives

At the end of this chapter, you will be able to:

- describe and adopt spate irrigation
- explain the operation principles of surge flow and cablegation

4.1 Spate irrigation

Floodwater diversion or spate irrigation techniques are those, which force the water to leave its natural course, which it would not do without manipulation (Critchley et al. 1992). Spate irrigation, or diversion of flood flow from highlands into lowlands and wadis (ephemeral river channels) has a long history in the Horn of Africa, and still forms the livelihood base for rural communities in arid parts of Eritrea and the upper Rift Valley in Ethiopia (SIWI 2001). Storm-floods are harvested from rainfall-rich highlands, and diverted into levelled basins in the arid lowlands. In the arid and semi-arid areas of Ethiopia, water is an important limiting factor to crop growth (Haile and Tsegaye 2002). Floodwater harvesting has helped convert dry valleys and flood plains into more productive areas; growing a variety of crops such as fruit trees, forage crops and cereals (Critchley et al. 1992).

Spate irrigation is practised in the drought-prone regions of Dodoma, Singida, Tabora, Shinyanga, Arusha and Mwanza of Tanzania with the objective and achievement of crop yield increase from 1 to 4 t/ha. However, most of the structures were damaged during the El-Nino rains of 1997/98. There are major lessons to be learned from what happened during El-Nino rains (Hatibu et al. 2000).

Spate diversion systems have also been practised in Turkana District of Kenya with good results (Critchley et al. 1992). The diversion (water spreading) schemes consist of earthen embankments that divert part of the flow of wadis into channels, leading the discharge to plains where bunds spread and impound the flow. Some of these schemes are for fodder, and others for crops. While there is a considerable range, the schemes are generally expensive (approximately USD 1000/ha) to construct and bund breakages are a continuous problem. The different characteristics of each site make engineering design particularly problematic.

4.2 Surge flow

In 1979, Stringham and Keller (1979) reported a new approach for automating surface irrigation systems in which problems with slow advance and excessive surface runoff occur. The approach was called 'surge flow' to describe the hydraulic regime of the flow over the field. Under the surge flow regime, irrigation is accomplished through a series of individual pulses of water onto the field (Figure 36). Instead of providing a continuous flow onto the field for say six hours, a surge flow regime would apply six 1 hour 'surges'. Each surge is characterized by a cycle time and a cycle ratio. The cycle time is comprised of an on-time and an off-time related by the cycle ratio, which is the ratio of on-time to the cycle time. The cycle time can range from as little as one minute to several hours. Cycle ratios typically range from 0.25 to 0.75. By regulating these two parameters, a wide range of surge flow regimes can be produced, which can significantly improve irrigation efficiency and uniformity.

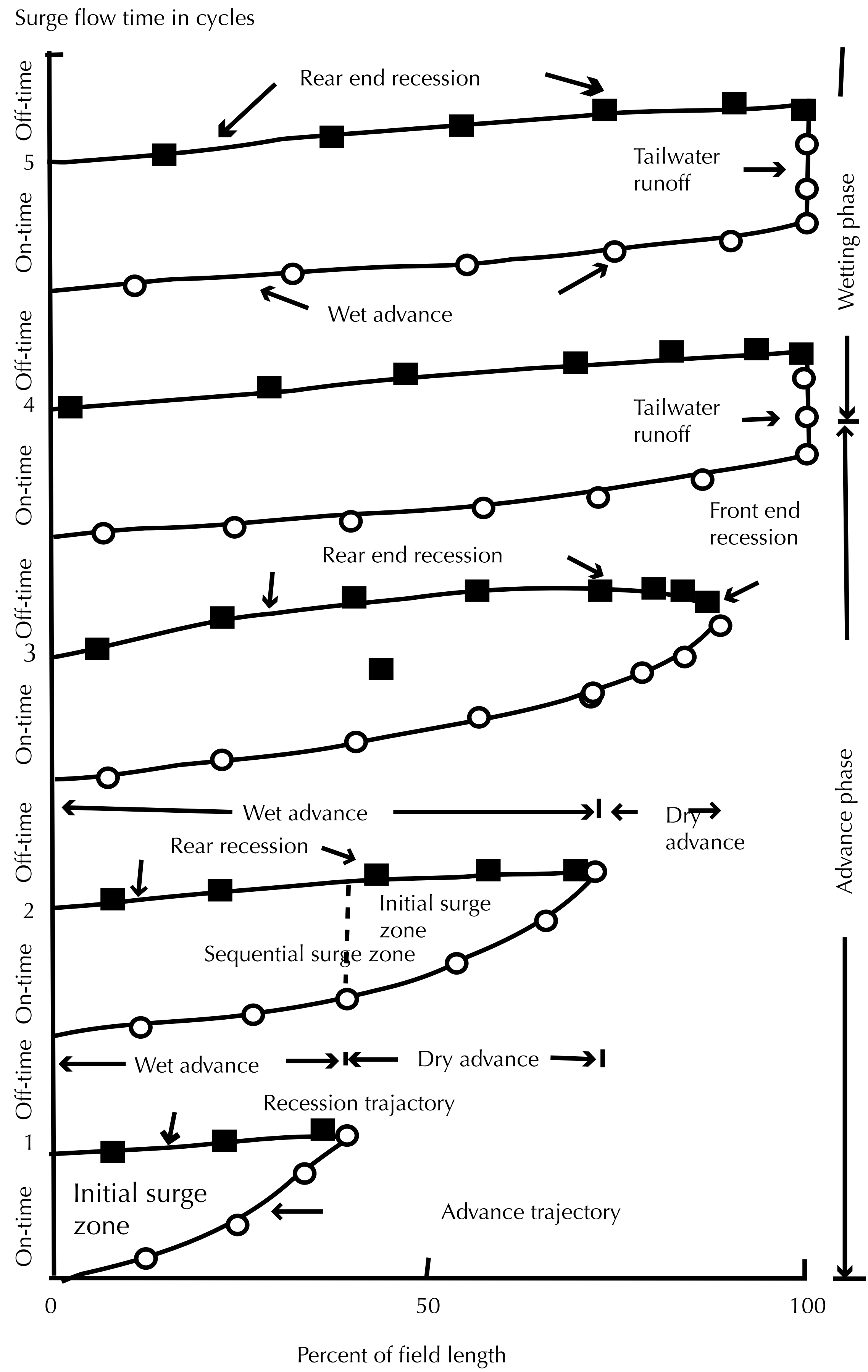

Figure 36. *Typical surge flow advance-recession trajectory.*

4.2.1 Effects of surging on infiltration

The effects of surge irrigation vary depending on the selection of cycle time, cycle ratio and discharge. But in nearly every case, the intermittent application significantly reduces infiltration rates and/or substantially reduces the time necessary for the infiltration rates to approach the final or 'basic' rate. To affect infiltration rates, the flow must completely drain from the field between surges. If the period between surges is too short, the individual surges overlap or coalesce and the infiltration effects are generally not created.

Research shows that the surging effect on infiltration is primarily due to the consolidation of the thin layer of fine material deposited in the bottom of the furrow or on the border (or basin surface) by the destruction of soil aggregate and erosion caused by the water flow. As the water drains from the field between surges, the negative pressure that develops in the soil consolidates the surface layer, collapsing the larger pores, attracting small particles into the lattice between larger particles, and orienting clay and silt into a layered structure. As a result the permeability of the field surface is reduced and thereafter infiltration rates are lowered. The reduction in surface permeability seems to be more pronounced in sandy loam soils than in clay loam soils. The rate of aggregate wetting and erosion affect the thickness and extent of the surface layer.

Evidence of the consolidation of the fine layer between surges can usually be observed in the field 5–15 minutes after the water has completely drained from the field. Tension cracks form between the layers of fine material and those less disturbed by the flow. When water is again introduced into the field, sediments are deposited in these cracks as they begin to swell shut, thereby further compacting the surface layer.

The effect of reducing the infiltration rates over at least a portion of the field is that advance rates are increased. Generally, less water is required to complete the advance phase by surge flow than with continuous flow. Surging is often the only way to complete the advance phase in high intake conditions like those following planting or cultivation. As a result, intake opportunity times over the field are more uniform. However, since results will vary among soils, type of surface irrigation, and the surge flow configuration, tests should be conducted in areas where experience is lacking in order to establish the feasibility and format for using surge flow.

4.2.2 Effects of surging on surface flow hydraulics

The hydraulic regime of a surge flow system is composed of two parts: (1) the distinct surge phase and (2) the coalesced surge phase. Each pulse of water advances and recedes over a portion or the entire field as shown in Figure 36. This phase is used during the advance phase for the entire field, i.e. during the time needed to wet the entire surface of the field. Surges during the distinct phase must be of sufficient duration and discharge to fill cracks and depression storage along the pathway so that there is enough volume and energy to continue advancing at an adequate rate over the succeeding field section, but short enough to limit cumulative intake and maximize or minimize the infiltration reduction.

In the coalesced phase, the individual surges run together, overlap and result in a nearly steady flow in the downstream sections of the field. In this situation, the flow rate below the point of convergence is about half of the instantaneous rate at the field inlet. If the cycle ratios are reduced, the flow that the continuous flow reaches will be correspondingly reduced. It is therefore possible to adjust the cycle ratios until practically no surface runoff occurs. Thus, by combining the distinct and coalesced phases of surge flow into one system, the solution of the long-standing surface irrigation dilemma is available, a high flow for the advance phase and a low flow for the wetting phase.

4.2.3 Surge flow systems

There are basically two field systems commercially available for surge flow, both limited at present to furrow irrigation. The first is shown in Figure 37 and will be described here as the 'dual line' system (Humphreys 1987). Water is supplied to the field generally through a buried pipeline, which connects to surface gated pipe through a riser and valve. The valve, shown schematically in Figure 38, is automated to switch the flow between two sets. Surging is accomplished by alternating the flow between the two sets. When these two are finished, the entire flow is directed to another riser and valve by the irrigator. The dual line system is in widespread use in the USA where irrigators already have a gated pipe furrow irrigation system in place. Farmers only need to purchase the automated valve to implement fully a surge flow regime. The costs for these systems where the distribution and gated pipe already exist can be as low as USD 50 per hectare.

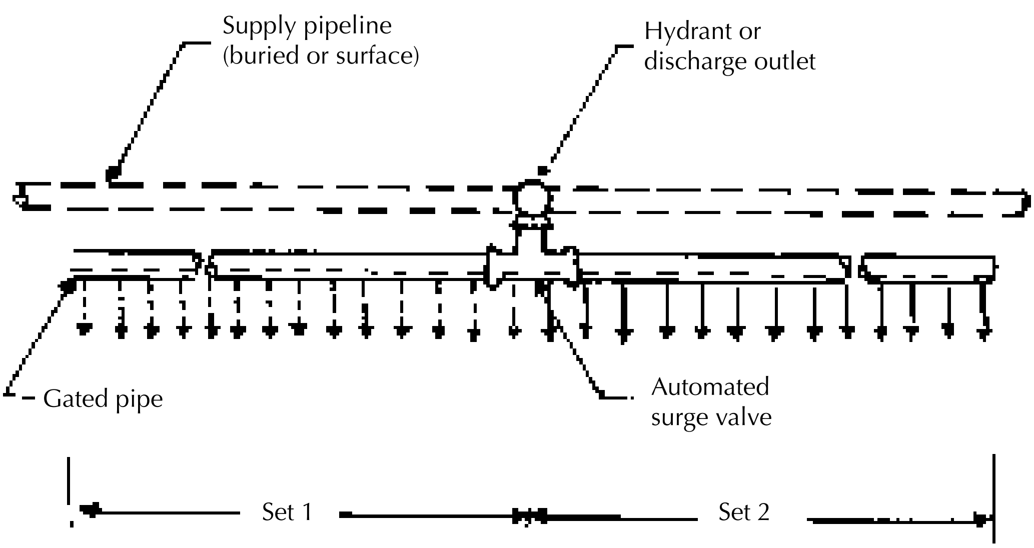

Figure 37. *Schematic diagram of a dual line surge flow furrow irrigation system (redrawn from Humpherys 1987).*

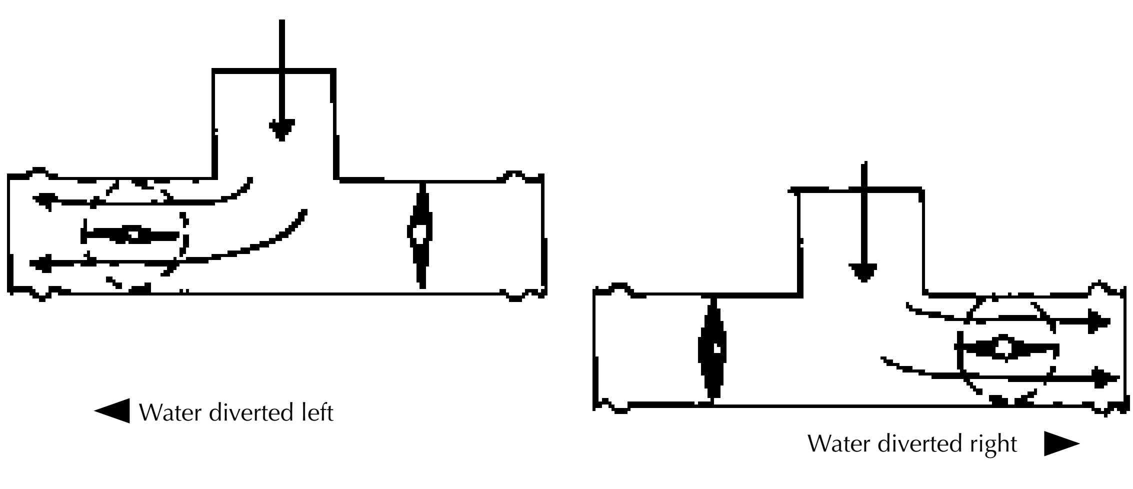

Figure 38. *Configuration of one automated surge flow valve for the dual line system (redrawn from Humpherys 1987).*

The second field configuration is the single line system shown in Figure 39. A single gated pipe is connected to the water supply and individual outlets along with pipe are controlled by small hydraulic, pneumatic, or electric valves which are organized in banks and sets as shown and controlled by a single controller.

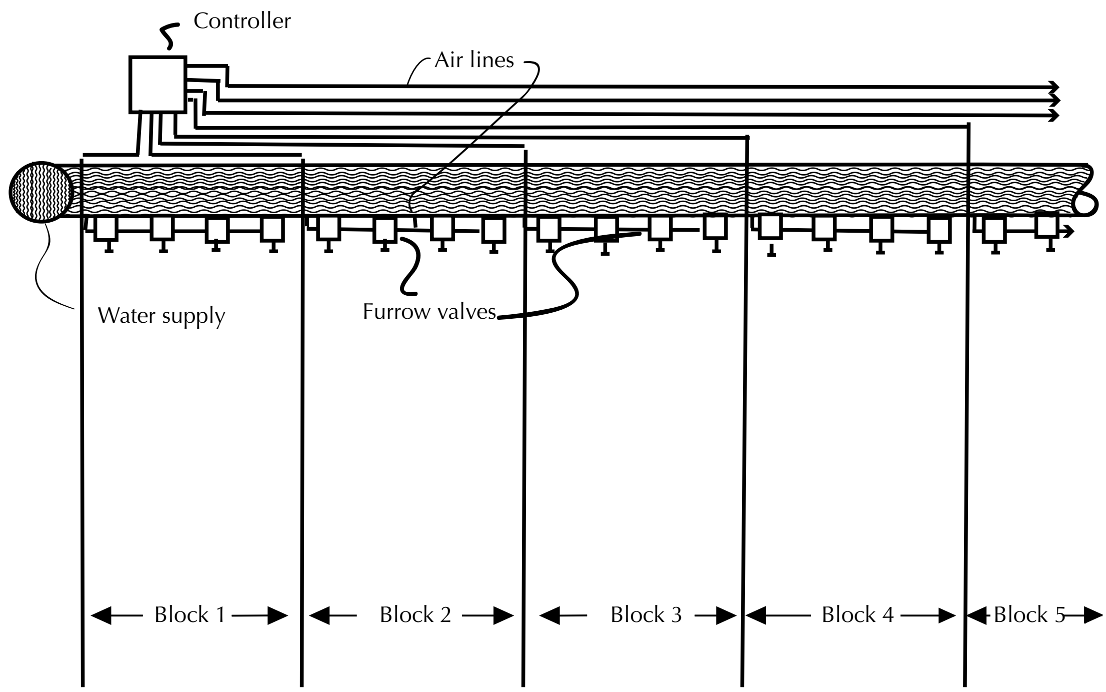

Figure 39. *Schematic of the single line surge flow system (redrawn from Humpherys 1987).*

The single line system is economical for new systems where all of the field facilities need to be provided. It also tends to be more economical where only the gated pipe is available and the decision of the irrigator is whether or not to put in a buried supply line and then use the bi-directional valve or to put automated gates on the gated pipe and use the single line concept. In many cases, the single line system will be more flexible than a dual line system in terms of irrigating an entire field.

4.3 Cablegation

The cablegation system illustrated graphically in Figure 40 was developed by the Soil and Water Management Research Unit of the US Department of Agriculture's laboratory at Kimberly, Idaho (Kemper et al. 1985). The system involves a pipe with fixed or adjustable outlets that are placed on a precise gradient. An adjustable plug is placed inside the pipe and connected by a cable to a winch-type unit at the pipe inlet. The winch unit includes a speed control feature.

Hydraulically, a cablegation system operates in the free surface flow regime upstream of the travelling plug except immediately adjacent to it. In the region near the plug, the flow is slowed and expands to fill the pipe. Thus, in the uniform open channel flow region of the pipe, the water surface is below the outlets, which are therefore shut off from the field. Near the plug, the water level rises above the outlets to supply the field. The unique feature of the cablegation system is the high outlet flows nearer the plug. This feature gives the advance phase discharge needed to facilitate field coverage. As the plug moves downstream, the outlet flow is cutback to allow soaking time without causing excessive surface runoff.

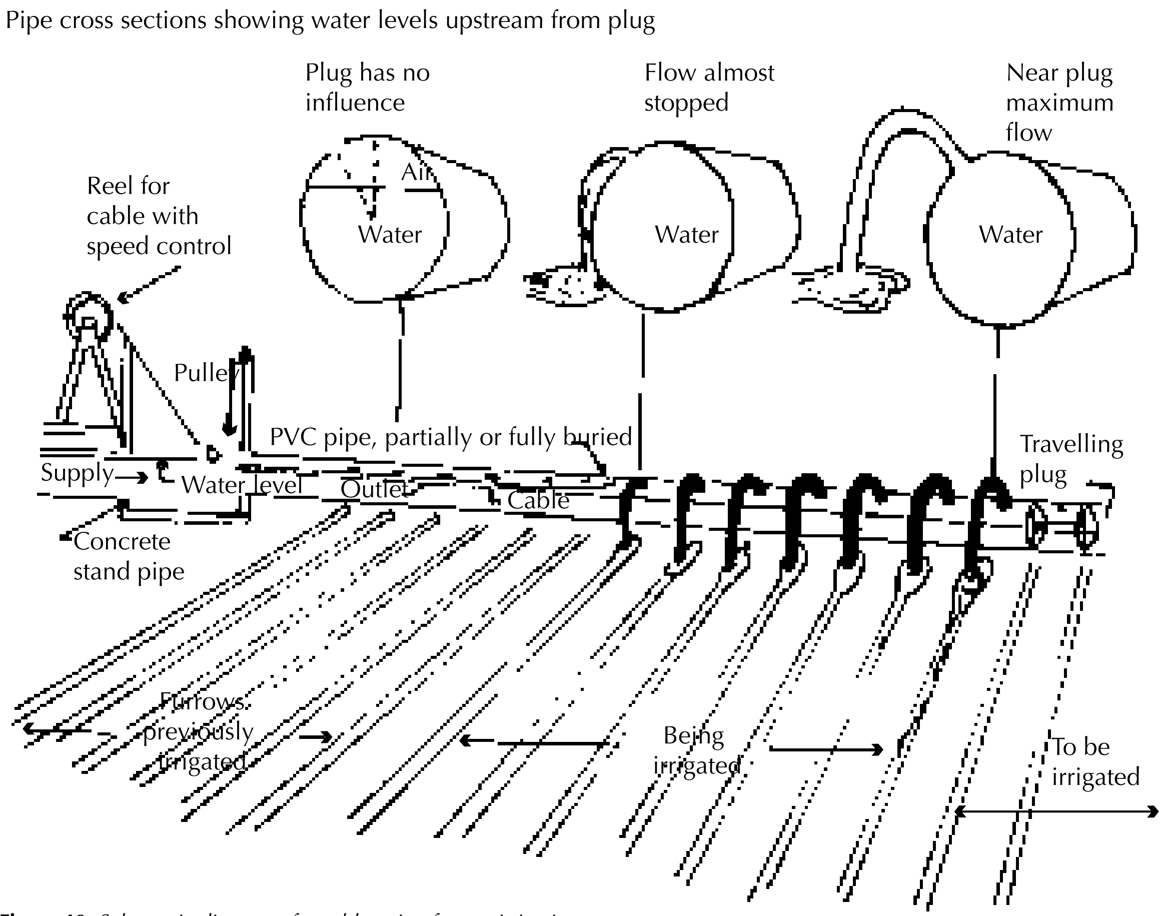

Figure 40. *Schematic diagram of a cablegation furrow irrigation system.*

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Module 5 – Part II

Irrigation methods: Drip irrigation—Options for smallholders

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Table of Contents

Chapter 1 What is drip irrigation?

Chapter objectives

Upon the completion of this chapter, you will be able to:

- define drip irrigation
- explain principles of drip irrigation
- describe the advantages of drip irrigation
- understand problems associated with drip irrigation

1.1 Principles of drip irrigation

Drip irrigation involves supplying water to the soil very close to the plants at very low flow rates (0.5–10 litre/hr) from a plastic pipe fitted with outlets (drip emitters) (Figure 1). The basic concept underlying the drip irrigation method is to maintain a wet bulb of soil in which plant roots suck water (Figure 2). Only the part of the soil immediately surrounding the plant is wetted. The volume and shape of the wet bulb irrigated by each drip emitter are a function of the characteristics of the soil (texture and hydraulic conductivity) and the discharge rate of the drip emitter. Applications are usually frequent (every 1–3 days) to maintain soil water content in the bulb close to field capacity (Howell and Hiler 1974; Wu 1975; Isaya 2001; Verma 2003).

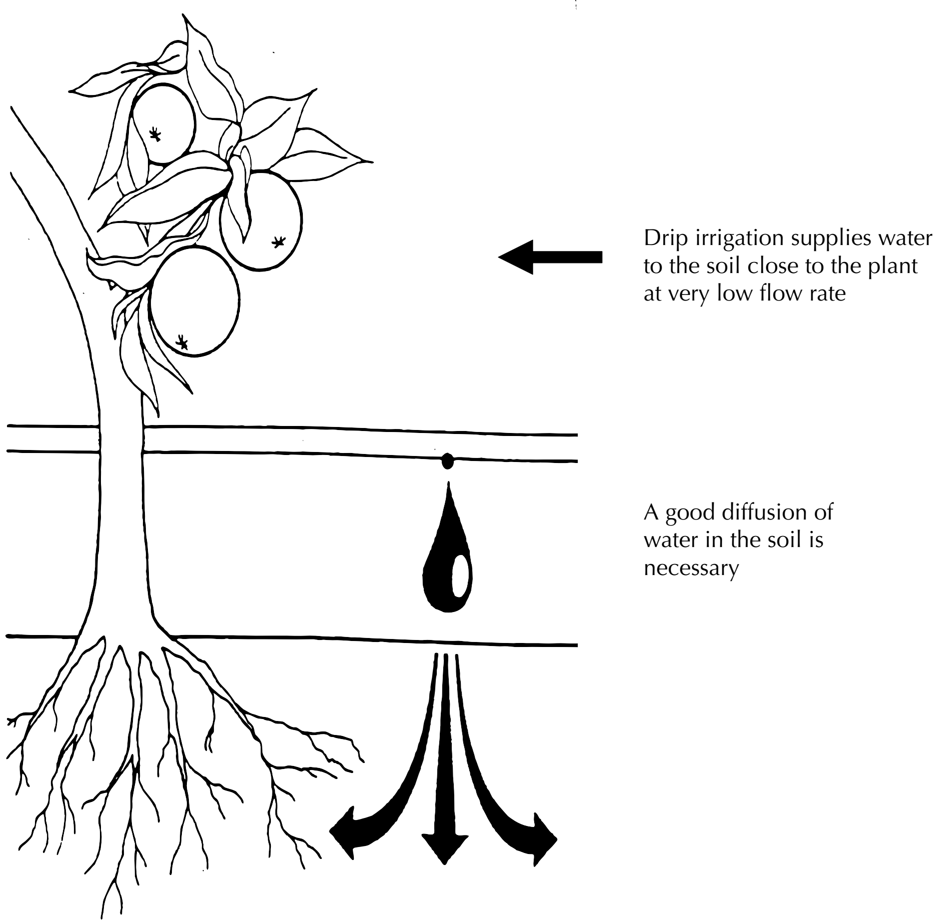
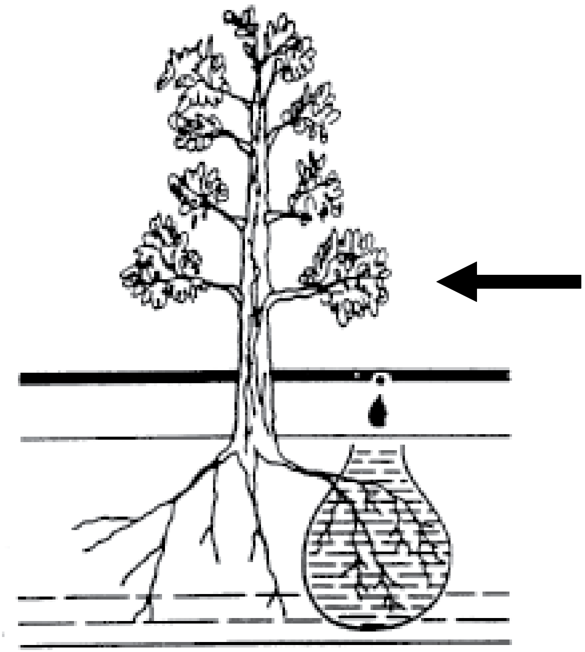


Figure 1. *Principles of drip irrigation.*



Drip irrigation maintains a wet bulb of soil in which plants suck water. Only a part of the roots is active

Figure 2. *Principles of drip irrigation (continued).*

1.2 Advantages of drip irrigation

The following advantages are accompanied with the use of drip irrigation (Kadyampakeni 2004):

1 ***More efficient use of water***: Compared to surface irrigation and sprinkler methods (with efficiencies of 50–75% in high-management systems), drip irrigation can achieve 90–95% efficiency. This is because percolation losses are minimal and direct evaporation from the soil surface and water uptake by weeds are reduced by not wetting the entire soil surface between plants (Polak et al. 1997a, b; Narayanamoorthy and Deshpande 1998; Narayanamoorthy 1999).

2 ***Reduced cost for fertilizers***: Precise application of nutrients is possible using drip irrigation. Fertilizer costs and nitrate losses can be reduced considerably when the fertilizers are applied through the irrigation water (termed fertigation). Nutrient applications can be better timed to coincide with plant needs since dressing can be carried out frequently in small amounts and fertilizers are brought to the immediate vicinity of the active roots.

3 ***Reduced labour demand***: Water application is less labour demanding compared to surface or bucket irrigation. Cultural practices such as weeding can be performed when the plants are being irrigated (Polak et al. 1997a, b; Narayanamoorthy and Deshpande 1998).

4. ***Low energy requirement***: A drip irrigation system requires less energy than a conventional pressurized system as it increases irrigation efficiency and therefore requires less water to be pumped. Compared to other pressurized systems, savings are also made because of the lower operational water pressure required for drip systems.

5. ***Reduced salinity risk***: The drip lines are placed close to a row of plants and the root zone tends to be relatively free of salt accumulations as the salts always accumulate towards the edge of the wetted soil bulb. The accumulation of salts on a surface-irrigated field tends to be right in the middle of the root zone.

1.3 Problems associated with drip irrigation

The possible problems that can be associated with drip irrigation are as follows:

1. ***Clogging of emitters***: Clogging of emitters is the most serious problem associated with drip irrigation. To prevent blockage, care should be taken to filter the water properly before use, depending on the particular particle size and type of suspended material contained in the irrigation water. It is also necessary to flush drip lines at least once a month (Howell and Hiler 1974; Wu 1975; Isaya and Sijali 2001).
2. ***Cost***: Conventional drip irrigation systems typically cost USD 5000–10,000 per hectare, or more, when installed in East Africa. However, recent advances have introduced some adaptations in the systems that are making them accessible to small-scale farmers. In Chapter 3, we describe simple drip irrigation systems, which would cost a farmer USD 15 to cover 15 m^2, or USD 200–400 for a bigger system covering 500 m^2.
3. ***Water management***: When practising drip irrigation, farmers do not see the water. This often results in over irrigation and the loss of the benefits of high irrigation efficiency. Over-irrigation will also make the soil excessively wet and therefore promote disease, weed growth and nutrient leaching. However, smallholder farmers learn quickly and adopt drip irrigation technology in the light of their practical experiences in using the various methods to monitor water application (Sivanappan 1977; van Leeuwen 2002).
4. ***Restricted root zone***: Plant root activity is limited to the soil bulbs wetted by the drip emitters; a much smaller soil volume than that wetted by full-coverage sprinkler or surface irrigation systems. Thus, if a drip irrigation installation fails (clogging), the crops will suffer more from drought than crops watered by sprinkler or surface irrigation. Under drip irrigation the confinement of roots to a small soil volume means less available soil water storage for the plants. As a result of this it is recommended to continue irrigation even after a rain.

Chapter 2 Components of drip irrigation systems

Chapter objective

After reading and understanding this chapter, you will be able to:

- explain the different components of drip irrigation system

A drip irrigation system is comprised of several components (Wu 1975; Taffa 1987; Sivanappan 1988; NCPA 1990). The basic components (see Figures 3 and 4) of any drip irrigation system are:

- Water source to provide the amount of water required at the necessary pressure to push water out of the drip emitters;
- Filter to remove particles from the irrigation water that may clog the drip emitters
- Control valve to open and shut off the water;
- Main lines in polyethylene to carry and distribute water to the laterals lines;
- Lateral lines in polyethylene to carry the water and distribute it to the drip emitters. The usual diameter of these lines range between 12 and 20 mm.

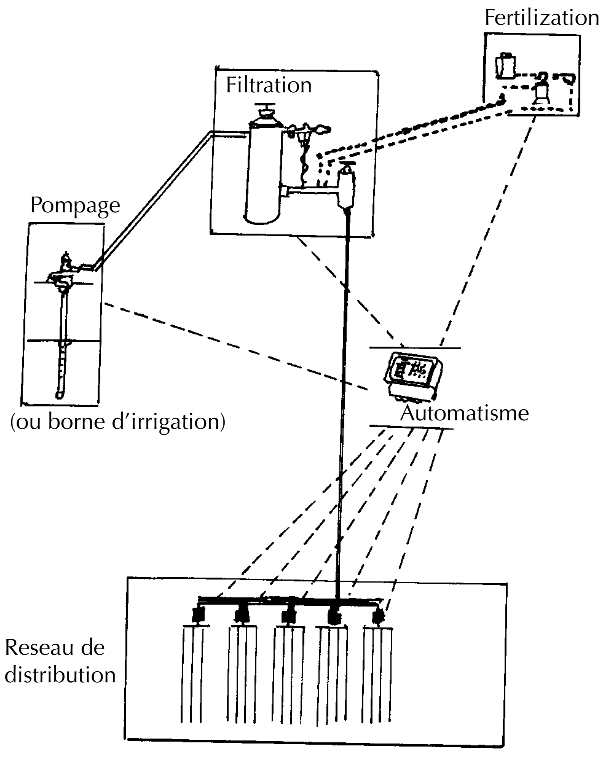


Figure 3. *A conventional drip irrigation system (used by large commercial farmers).*

Additional components of sophisticated systems are:

- Injection equipment to apply fertilizers;
- Pressure regulators;
- Flow metres to measure the amount of water flowing in the system;
- Centralized computer system for automatic irrigation.

The hydraulic design (lengths and diameters of main and lateral lines, calculation of required water pressure) of conventional drip irrigation system is beyond the scope of this manual. Chapter 3 gives a description of ready to install low cost drip irrigation kits for smallholders.

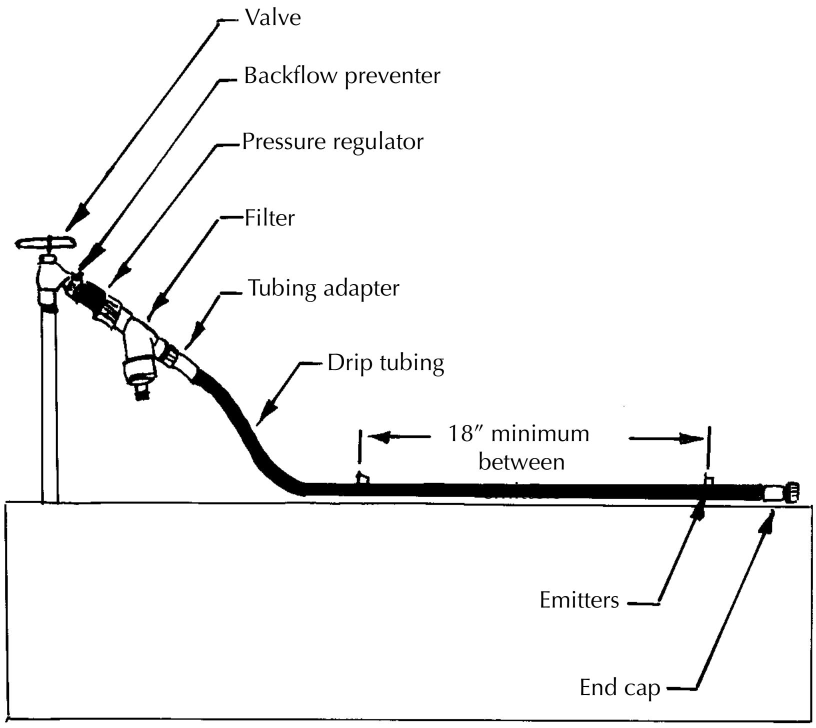


Figure 4. *Illustration of a very simple drip system.*

Main lines

Main lines carry water to the drip laterals. They are usually made of plastic. The size depends on the required water flow in the laterals served. Large main lines can be connected to smaller sub-main lines, which are in turn connected to the drip laterals.

Drip lateral lines

Drip lines are made from polyethylene tubes. The most common drip line sizes are in the range of 12–20 mm in diameter. The density of plants in the field usually determines spacing between emitters; only after this the soil type (texture) is considered (Figure 5). Emitter spacing usually ranges from 30 cm for plants like onions and carrots to 100 cm for fruit trees.

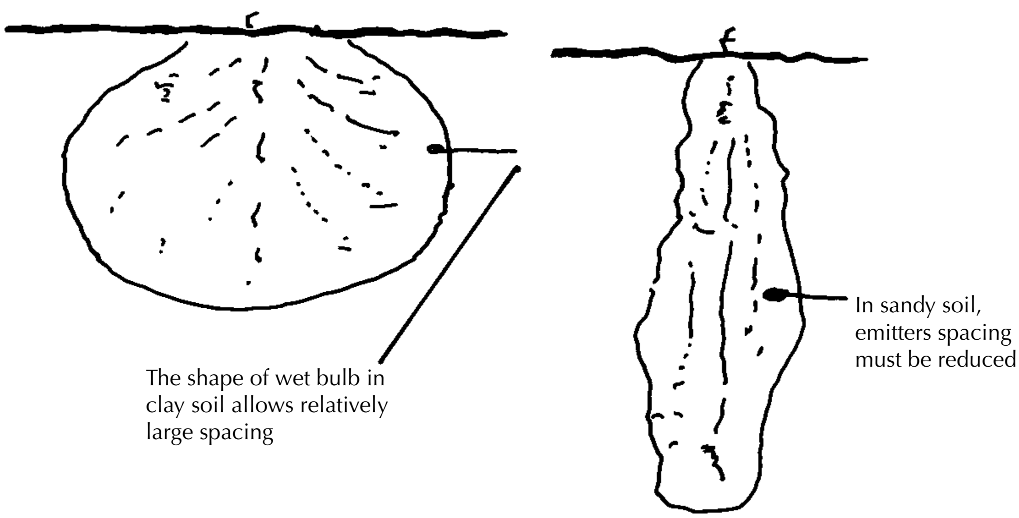


Figure 5. *Spacing of emitters and soil texture.*

Emitters

The drip emitters control the flow from the lateral into the soil. Common drip emitters have discharge in the range 1–15 litres/hr at the standard pressure of 1 atmosphere (= 10 m = 1 bar). They must distribute the water uniformly. The variation in discharge between the emitters in the whole field should not exceed 20%.

Another important aspect of drip emitters is their resistance to clogging at the water pressure operational for the system. Information on the emitter's resistance to clogging is supplied by manufacturers and research institutions, but should be supported by local experience. Frequent inspection of emitters to identify clogged ones is necessary. A clogged emitter can be repaired by rubbing it vigorously with one's fingers, blowing in it, or trying to force water out of the outlet.

Five types of drip emitters are available:

- *In-line drip emitters* (Figure 6)

In this type, individual emitters are inserted into the drip lateral line by cutting segments of it.

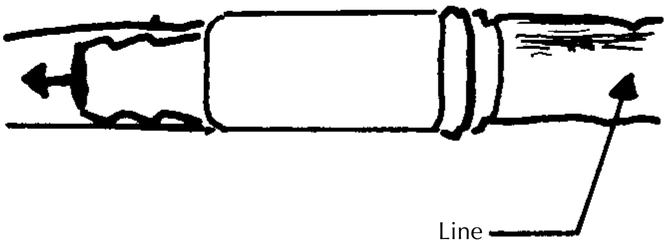


Figure 6. *In-line emitter.*

Integral drip emitters

In the integral type, the drip emitters are welded by manufacturer to the inner wall of the tube and come as continuous rolls (integral drip lines) with outlets at predetermined intervals. Drip lines are available in various diameters, wall thickness and emitter spacing.

- *Button-type emitters* (Figure 7)

In this type the drip emitters are designed to be inserted directly into the wall of the lateral line either at predetermined intervals or in clusters. The button-type emitters are mainly used in orchard and pot plant (green houses).

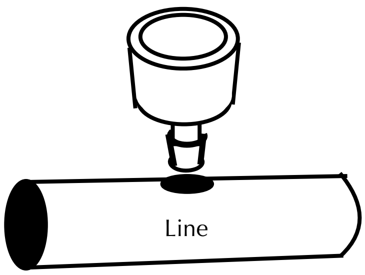


Figure. 7. *Button type emitter.*

- *Tapes* (Figure 8)

Tapes are manufactured plastic tubes that ensure both water conveyance and water distribution through small holes (= emitters). Flat when not in use, the water pressure keeps them open when in use. Spacing between emitters ranges between 20 and 100 cm.

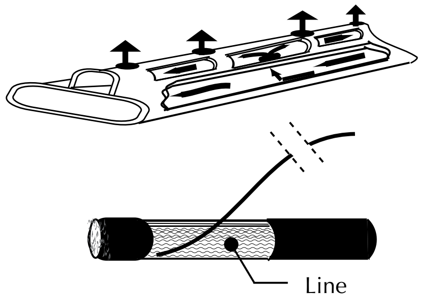


Figure. 8. *Drip tape.*

- Home made emitters

An old and efficient way to make emitters is to insert sections of micro-tube (0.6–1 mm in diameter) into holes punched in the lateral line, then adjusting the micro-tube length to provide the desired discharge rate (Figure 9).

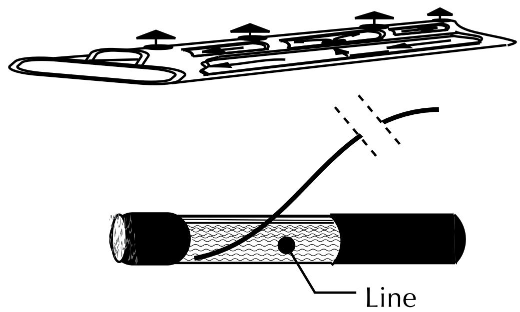


Figure 9. *Micro tube.*

Simple drip emitters can be made by punching holes manually into the lateral tubes. To make such perforations as uniform as possible, a standard hole-puncher is used (but many farmers simply use a nail). To prevent excessive flow or blockage of the perforations, the holes can be covered with tight-fitting collars made by cutting short sections of the same pipe that is used for the laterals and slipping them over the holes (Figure 10).

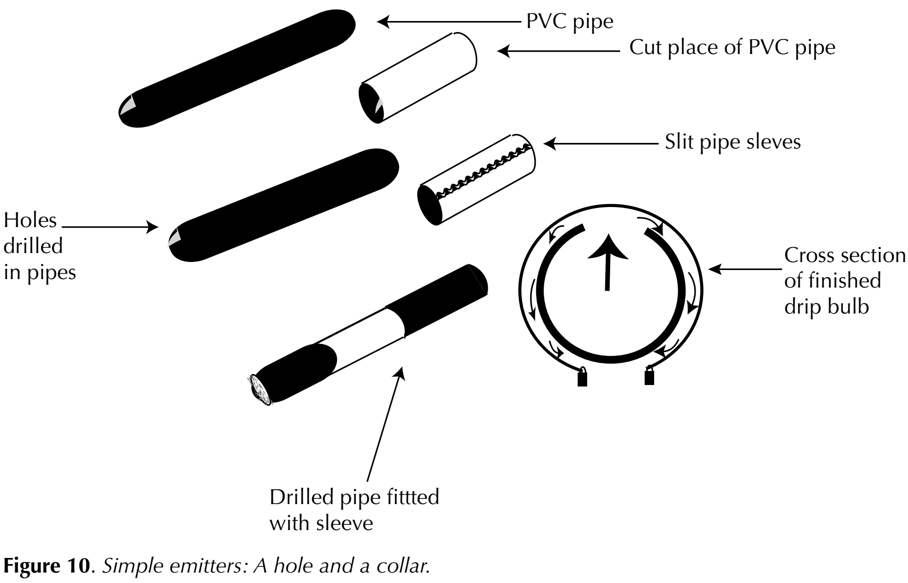


Figure 10. *Simple emitters: A hole and a collar.*

Chapter 3 Low cost drip irrigation systems for smallholders

Chapter objectives

Upon completion of this chapter, you will be able to:

- describe the components of drip irrigation systems
- explain the general features
- maintain the system
- understand and facilitate the tips provided on water management and planting
- describe the drip irrigation systems

3.1 Introduction

The efficient use of water is seen as a key to crop production in arid and semi-arid areas in sub-Sahara Africa (van Leeuwen 2002). This is increasingly true because of ever-increasing populations and demand for food production, coupled with growing competition for water. For smallholder farmers, drip irrigation provides a means of maximizing returns on their cropland by increasing the agricultural production per unit of land and water and increasing cropping intensity by growing a crop during the dry season. The development of low-head emitters and simple filtration has reduced much of the initial capital investment necessary, making small-scale drip irrigation systems affordable to smallholder farmers. Research and experience is helping to provide tailor-made drip irrigation systems to suit different field and water conditions.

Drip irrigation systems are normally used for cash crops (vegetables, fruits). Smallholder drip irrigation systems are being used in some parts of Africa; for example, the Chapin bucket kits are being used in Kenya, Tanzania, Malawi, Zambia and Uganda. The Waterboys bucket has mainly been used in Uganda, although a number of kits are in use in Kenya and Tanzania. Elsewhere in the world, for example, in India, resource-poor farmers have used drip irrigation systems with reported success. Most smallholder drip irrigation systems operate under low pressure such as 1–5 m head (Polak et al. 1997a, b; Narayanamoorthy 1999). The coverage area determines the water pressure required to overcome pressure losses associated with water delivery and filtration. In low-pressure systems, water containers such as buckets or drums, raised 0.5–1.5 m above the ground, are used as header water tanks to enable the filling of the container either manually (bucket) or using pumps.

The smallholder drip irrigation systems presented in this chapter are grouped into two categories, namely: bucket and drum drip irrigation kits (Table 1).

Table 1. *Characteristics of bucket and drum drip irrigation system*

System type	Head required	Area covered: m^2	Examples given
Bucket system	1 m	Less than 20	Chapin and IDE
Drum system	1–5 m	20–1000	KARI and IDE

3.2 General features

Low cost drip irrigation systems consist of:

- Water storage–usually a bucket or a drum,

- Water filtration
- Conveyance and water application lines with emitters (PE, 12 or 20 mm)
- Valves

Details of some drip irrigation systems used by smallholders in Africa and India are presented in this chapter (Sivanappan 1977; Polak et al. 1997a, b; van Leeuwen 2002).

Common preparation requirements and features are as follows:

- Prepare the area to be irrigated. This could be simple land preparation or involve the formation of planting beds (see box 1).
- For best results, drip systems are used to irrigate level beds. If the drip tubes go uphill, downhill or around corners, the system will not give equal water flow from each dripping outlet.
- Construct the water container stand. Ensure that it can support the weight of the container and water when full.
- Mount the water container on the stand so that the water outlet is at the height necessary to provide the water pressure required to operate the system.
- Mount the container water outlet, water filtration and flow regulator fittings.
- Lay the water distribution system components that connect the water container to the individual drip lines. Make sure that the open ends are closed to avoid foreign material entering the pipe.
- Unroll the drip lines and lay them along the full length of each row of plants to be irrigated.
- Connect the drip lines with the water distribution system (header pipes).
- Flush the system to remove any foreign matter that may have entered the pipeline.
- Close the end of the drip lateral lines.

It must be emphasized that any training or advice on the use of drip kit systems should not only cover actual kit installation and maintenance, but also all aspects of growing vegetables under drought conditions since the purpose is to increase farmers' yields and income. Thus training and advice should include lessons about bed preparation, composting, transplanting, irrigation water management and pest and disease control.

Box 1: Preparation of a planting bed

1. Lay out the planting bed depending on the length, spacing and number of the drip lines.
2. Excavate shallow trenches (15–30 cm deep) lengthwise where the row crops will be planted.
3. Place seedlings or seeds in the trench.
4. Add a 5–10 cm layer of fresh manure or compost on top of the planting material.
5. Level the ground to form a raised bed 10–20 cm above the aisles.

3.3 Maintaining the system

Ensure that only clean water is used in order to minimize the risk of clogging the filtration system. A filter screen will keep coarse particles from entering the drip lines. If there is fine silt in the water, or sand blowing in the air, a piece of cloth can be tied over the top of the bucket. Water can be poured through the cloth to keep the fine particles from entering the bucket.

Clean the filtration system at least twice a month. Inspect the emitters to identify clogged emitters at least once a week and unblock or replace any clogged emitters. Clogged drip emitters cause non-uniform application of water and result in non-uniform growth of the plants. A clogged emitter can be repaired by rubbing it vigorously with one's fingers, blowing in it, or trying to force water out of the outlet.

Flush the system at least once a month. The frequency can be increased or reduced depending on the amount of impurities in the irrigation water. Check leaks frequently and repair immediately. Take extra care during field operations, particularly weeding, to avoid cutting the drip lines. Take precautions to minimize the destruction of drip lines by termites and rodents (rats). When no longer in use, uninstall the components of the system and store them in a safe place.

3.4 Water management tips

To maintain an optimum soil-moisture regime it is necessary to apply the required amount of water at the right frequency. Shallow sandy soils require more frequent (1–2 day interval) irrigation and deep clay loam soils allow less frequent (2–4 day) irrigation. During the early stages of crop growth, the plant roots are shallow and therefore there is a need for more frequent irrigation and less water per irrigation event.

During the flowering or late vegetative stage of the crop, water consumption is highest and an adequate water regime is vital. Ensure that the crop does not experience moisture stress during this period. Crop water needs vary from 3 to 5 mm/day. Ensure that adequate amounts (depending on the area and crop growth stage) are applied. All leaks should be repaired quickly to prevent water wastage.

3.5 Planting tips

To ensure that the plants are planted where they will benefit most from the water supplied by the emitters, irrigate the field before planting and plant seedlings on the wetted circle. Most crops require manure at a rate of 1–2 handfuls and/or 1 tablespoon of double super phosphate per planting hole.

3.6 Description of systems

3.6.1 Bucket systems

In bucket kit drip irrigation, water flows into the drip lines from a bucket reservoir placed 0.5–1 m above the ground to provide the required water pressure. The efficient use of water that is possible with drip irrigation enables a farmer to grow vegetables using 30–60 litres of water daily during the crop-growing season. A bucket kit system comprising two 15-m long drip lines, can be used to grow 50 plants such as tomato, egg plant and similar crops requiring a spacing of 60 cm along the plant rows; 100 plants of spinach, cabbage, pepper and similar plants requiring a spacing of 30 cm along the plant rows; or 300 plants of onion, carrot and similar plants requiring a spacing of 10 cm.

The standard bucket kit system consists of two drip lines placed 0.5 m apart on a bed with a width of 1 m. A bucket is placed on a stand at one end of the bed and connected to the drip lines. These bucket kit systems can irrigate 10–20 m^2, depending on the length of the drip tube and plant spacing. The bucket should be filled once in the morning and once in the afternoon to supply 30–60 litres of water to the crop per day. The actual amount of water depends on crop water requirements and rainfall. In very dry areas and during the dry season 60 litres of water will be required per day.

There is a growing demand for bucket kits. For example, Chapin bucket kits are reported to be in use in over 80 countries worldwide and the demand is growing fast. By 2001, more than 5000 kits had been sold by KARI to Kenyan farmers who have adopted the bucket drip irrigation system. Despite their simplicity, bucket systems are extremely successful, saving precious water often fetched from long distances, and the labour needed to water each plant individually.

Three examples of bucket kits (Chapin, Waterboys and IDE) are described in this section. Each bucket kit comes with instructions on how to assemble it, to make the raised beds and how to manage them. In Kenya the average cost of a bucket kit is USD 15 (= Ethiopian birr, ETB 130).

Examples of bucket systems (ready to install bucket system kits)

Example 3.1 Chapin bucket system

Description of the system

Chapin bucket kits were developed by Chapin Living Water Foundation. This drip irrigation system (Figure 11) consists of a 20-litre bucket mounted 1 m above the ground and 30 m above drip tape.

Assembly instructions

1. Prepare the planting bed to be irrigated.
2. Mount a 20 or 30 litre bucket (supplied by the farmer), drill a 2.5 cm hole at the bottom 1 m above the ground.
3. Assemble the outlet from the bottom of the bucket by connecting the male adapter, rubber washer and female adapter.
4. Install the filter screen at the bottom of the bucket.
5. Install the two supply tubes running from the filter to the barb fittings.
6. Connect the 15-m drip irrigation tape through the drip lock fittings.

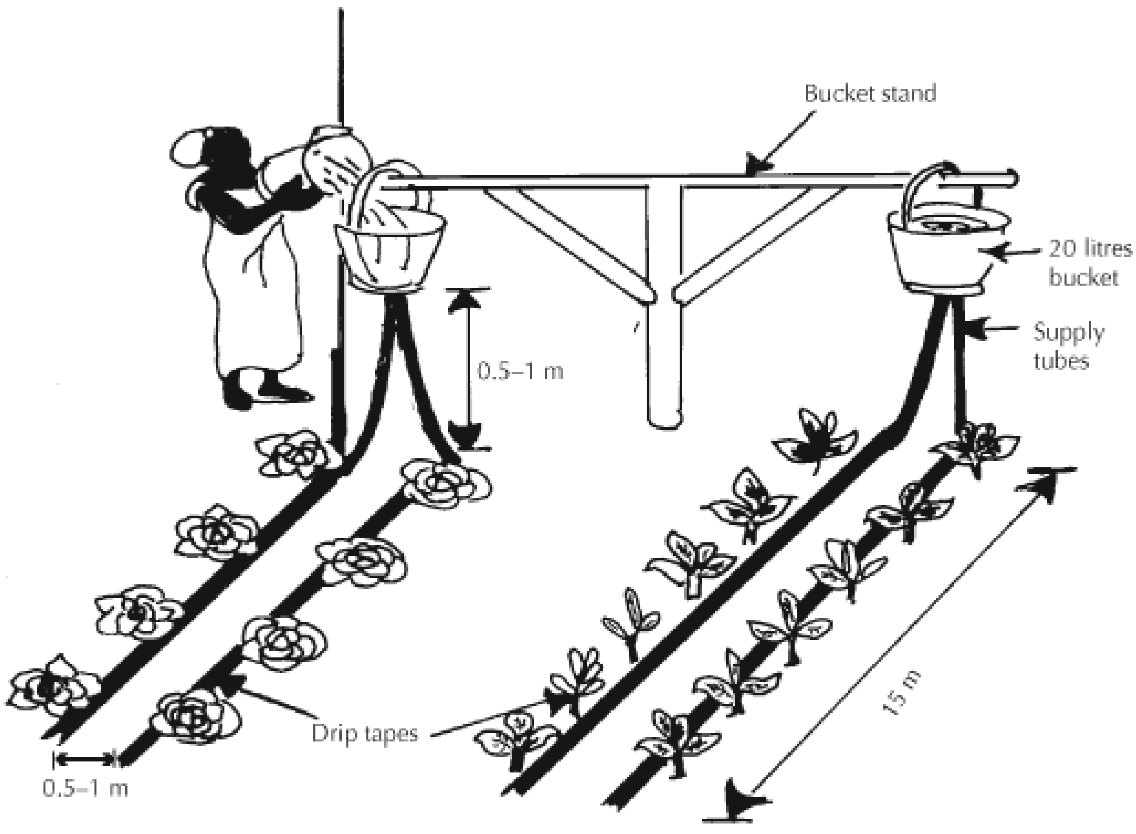


Figure 11. *Chapin bucket system with 2 lines.*

Example 3.2 IDE bucket system

Description of the system

The International Development Enterprise (IDE) of the USA has also designed and tested a bucket system. The IDE bucket drip irrigation system (Figure 12) consists of a 20 litres bucket, a valve, a filter, an end cap and a 10-m long, 12-mm diameter lateral line fitted with 26 micro-tubes, 13 on each side (emitter spacing 40 cm). All the pipes are pre-fitted and packed in a small box. The 13 micro-tube connections are spread over the length of the drip lateral at a spacing of 0.75 cm. Water from the bucket flows out like a small stream from all 26 micro-tubes and spreads out in a circular pattern. Four plants are planted in each of the circles and therefore a total of 104 plants can be watered by the IDE bucket system. The valve is used for flow regulation—giving the advantage that the bucket can be filled beforehand and irrigation started when required. The end cap is used to close the end of the lateral line (Polak et al. 1997a).

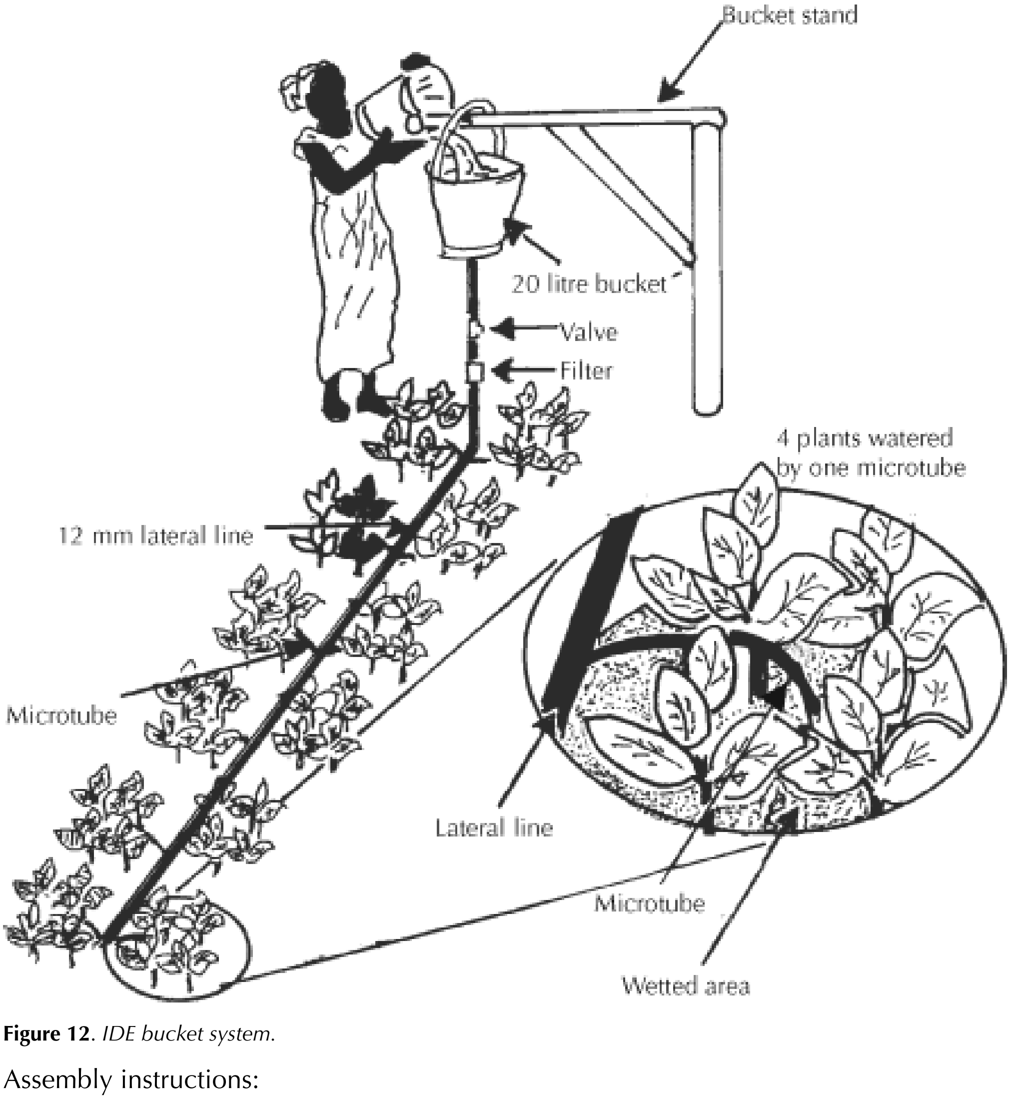


Figure 12. *IDE bucket system.*

Assembly instructions:

1. Prepare the planting bed.
2. Construct a bucket stand such that the bottom of the bucket is at a height of at least 0.5 m.
3. Unroll all the pipes and lay them on the ground.
4. Connect to the bucket with the snap-in collar provided at the bottom of the bucket.

Example 3.3 Waterboys system

Description of the system

Waterboys (Uganda) Ltd have adapted drip irrigation technology and developed a bucket kit for smallholder farmers in Uganda (Figure 13). The kit comprises of one 30-litre bucket (the bucket is part of the kit), and two, 10 m drip tubes connected to a water distribution manifold. The drip outlets in the standard kit are spaced at 30 cm. No filter is included in the Waterboys kit.

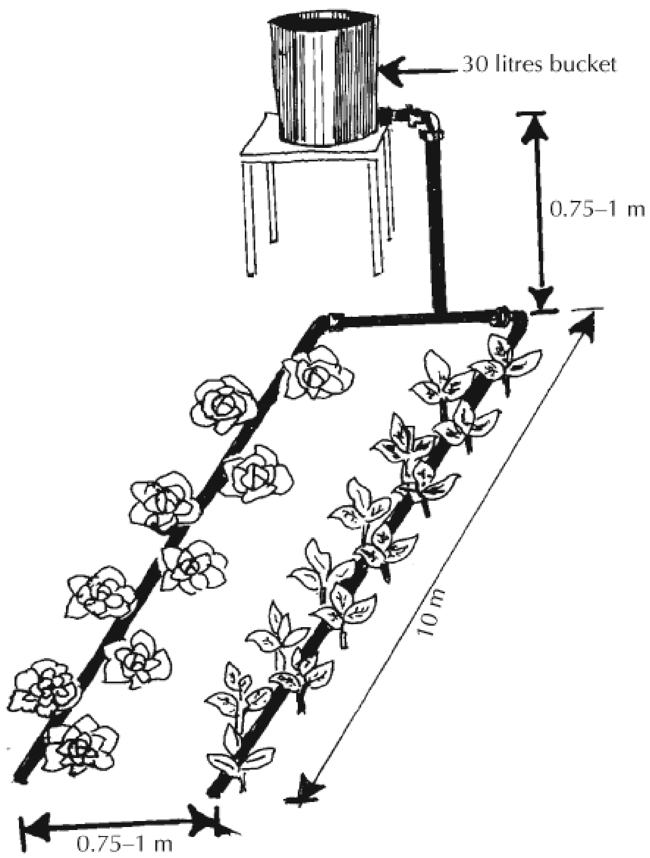


Figure 13. *Waterboys system.*

Assembly instructions:

1. Prepare the planting bed 1-m wide × 10-m long.
2. Construct a bucket stand.
3. Lay the pipes. Since all the pipes are already connected, you only need to lay them out on the bed.
4. Mount the bucket on its stand.
5. Connect the manifold to the bucket with a snap-in collar.
6. Connect the two drip lines to the tee.

Dealing with filtration

Since a filter is not included in the kit, the Waterboys bucket kit system requires water that has already been filtered for irrigation. This may not be realistic in many rural areas and even in some urban centres. Thus, if the water requires filtration, tie a clean cloth on the mouth of the bucket and always pour the water required for irrigation through it.

3.6.2 Drum systems

Drum systems operate under a low-pressure head of water (0.5–5 m). Mounting the drums on block supports raised at least 1 m above the planting surface is recommended. The higher the drum is placed the greater the area that can be irrigated. An area of up to 1000 m^2 can be covered by a drum system. In Kenya a drum system costs about USD 100 (= ETB 900).

The main advantage of drum systems is that a bigger area can be covered compared to the bucket system. This presents an economic advantage because of the number of plants per drum system. A drum system covering 5 beds each 1 m wide and 15 m long can be used to grow 250 plants (tomato, egg plant and similar plants) requiring a spacing of 60 cm along the plant rows); 500 plants (spinach, cabbage, kale, pepper and similar plants requiring a spacing of 30 cm along the plant rows); or 1500 plants (onion, carrot and similar plants) requiring a spacing of 10 cm.

The drum system also offers water storage and control through a control valve, making it possible to fill the drum for irrigating beforehand. The standard drum kit system comprises a drum, control valve, a manifold and drip lines. The drum should be filled with the valve in the closed position. To irrigate it is important to open the valve fully. This allows the water to be distributed quickly through the drip lines and allows for good water distribution. Two examples are presented: the KARI drum system from Kenya and the IDE drum used in India.

KARI[1] drum kit

Description of the system

This is a variation of the Chapin bucket kit and involves using a drum of about 200 litre capacity or the equivalent of 5 bucket drip irrigation systems. The development of this adaptation is credited to a farmer in Eldoret in the Rift Valley Province of Kenya who, after working with the bucket drip kits, connected an old drum to supply four drip lines. KARI improved on the drum adaptation by designing the manifold with four or five openings each serving two drip lines (Figure 14).

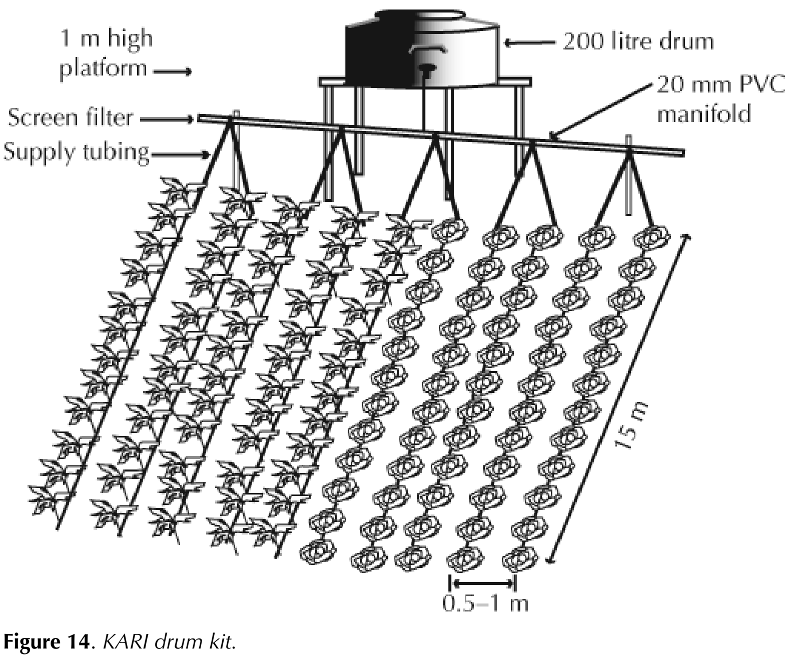


Figure 14. *KARI drum kit.*

1. KARI (Kenya Agricultural Research Institute).

Assembly instructions:

1. Prepare a rectangular area 7.5 wide × 16 m long.
2. Peg out the position of beds and paths to accommodate 5 beds each 1m wide × 15 m long. Leave a path 20 cm wide between the beds.
3. Connect the manifold by cutting the pipe into 3 pieces each 1.25 m long. These are connected to the 3 tees and the 2 bends connected at the ends. The 3 tees and 2 bends on each side of the PVC pipe are designed to be centrally located on the five planting beds. Depending on the location of the drum, a tee is connected to channel the water from the drum to the manifold.
4. Use PVC glue for leak-proof fitting and wait for the required duration to allow bonding.
5. Lay out the drip tapes on the beds, two lines per bed, and insert the filter plugs into the open ends of the outlets in the manifold.
6. Finally, connect one end of the connector tubing to the filter plug and insert the barb fitting to the other end. Connect the drip tube to the drip lock fitting.

IDE system

Description of the system

IDE (International Development Enterprises) of Colorado, USA, designed and tested a drum kit system, which can irrigate 520 vegetable plants (Figure 15). The drum kit consists of 130 pipes (1-mm diameter) called micro-tubes, fitted to 5 rows of 12-mm diameter PE laterals. Water flows out in a small stream from all 130 micro-tubes. The water then spreads out in a circular pattern to about 0.5-m radius. Four plants are planted in each of the circles. Field tests have been carried out on vegetables in the hill areas of Nepal and in Andhra Pradesh, India.

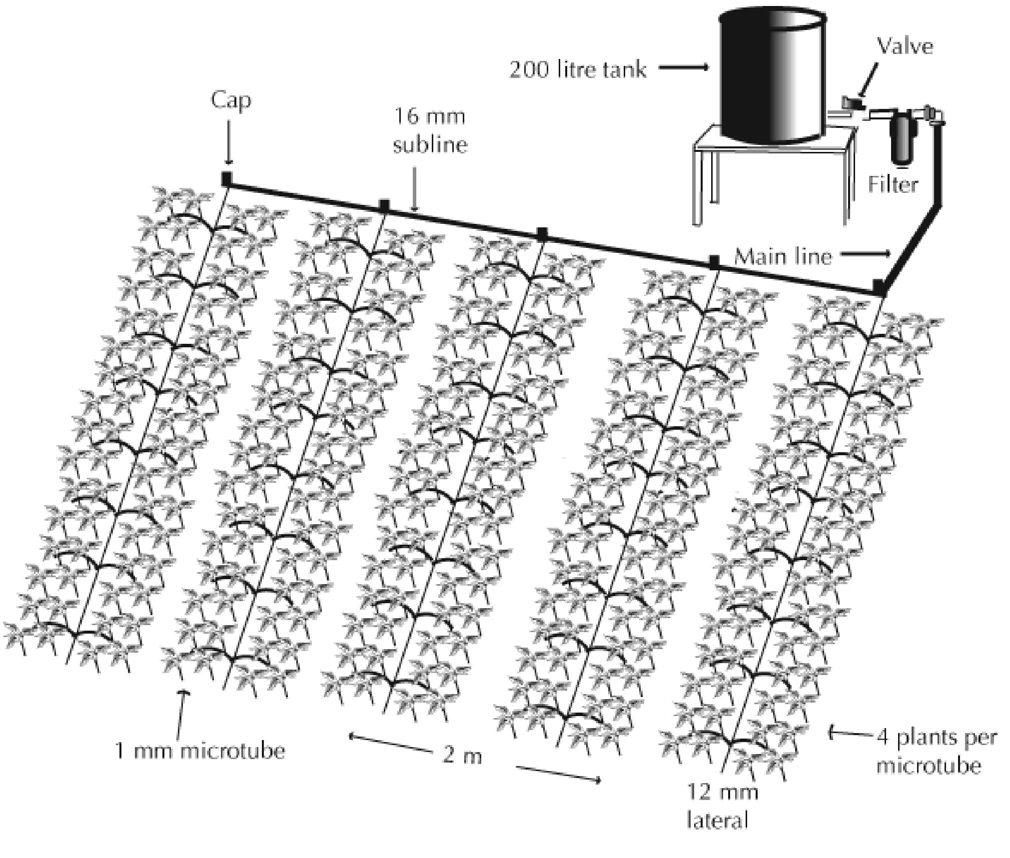


Figure 15. *IDE drum system.*

(See photos 1 and 2 in Appendix for arrangement and NETAFIM system).

Assembly instructions

1. Prepare the area to be irrigated.
2. Mount the drum.
3. Connect laterals to a 200-litre drum of water by a 16 mm-diameter pipe (submain).
4. Unroll all the pipes, lay them on the ground and connect to the drum. A manual is provided with the kit as a pictorial guide to correct installation and planting.

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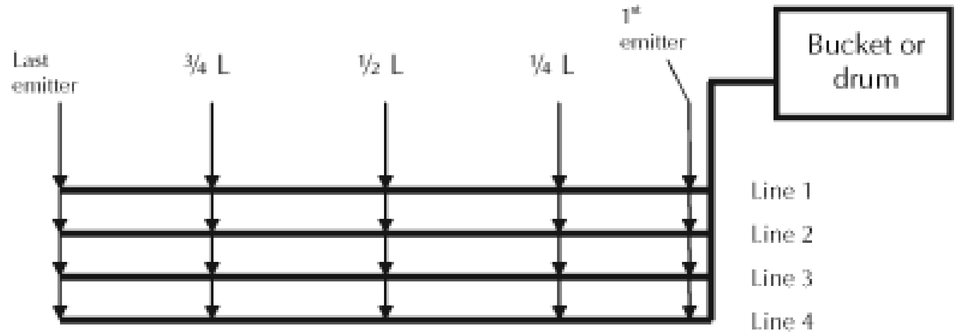
Appendix 1: Checking irrigation uniformity and cleaning emitters

Calculating irrigation uniformity

In the case of bucket or drum kit, measure out each lateral line, the discharge of at least 4 emitters; the total number of emitters checked must be at least 20.

Example



Average of all measured discharge

$$D_{average} = \frac{\text{Sum of 20 values}}{20}$$

Average of the 4 smallest measured discharges

$$D_{min} = \frac{\text{Sum of the 4 smallest values}}{4}$$

UC > 90: Uniformity is OK

90 < UC < 70: Flush the system

Uniformity coefficient

$$UC = \frac{D_{min}}{\text{average}} \times 100$$

UC < 70: Inspect the system to identify causes of clogging and clogged emitters. Fix clogged emitters by rubbing them vigorously with fingers, blowing in them, or trying to force water out of the outlet. If the cause of clogging is due to lime precipitate because of a high content of calcium carbonate in irrigation water, you can use HCl or H_2SO_4 at the dose of 0.05 litre for 10 litres, mix acid well with water of the drum/bucket and irrigate.

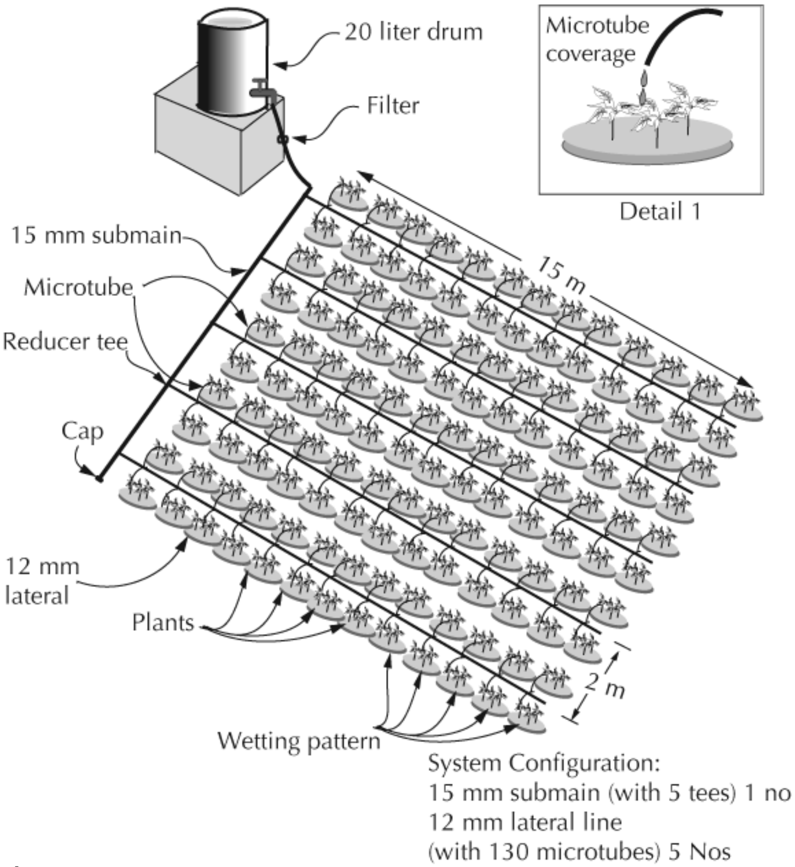


Photo 1. *IDE system*.

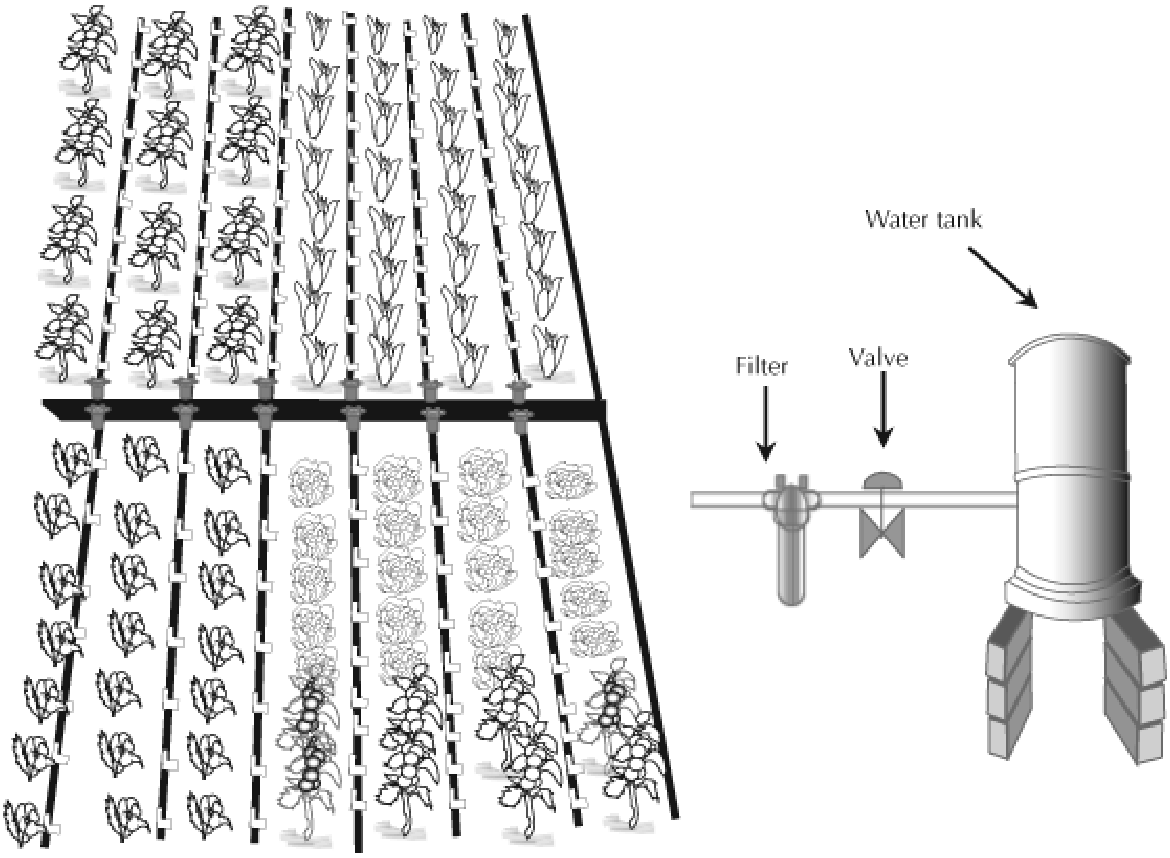


Photo 2. *NETAFIM system.*

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