A

Primer

On

Water Harvesting and Runoff Farming

by
W. Gerald Matlock
Director, Oracle Agricultural Center
Professor of Agricultural Engineering

and
Gordon R. Dutt
Professor of Soil and Water Science

Agricultural Engineering Department

College of Agriculture

University of Arizona

Tucson, Arizona

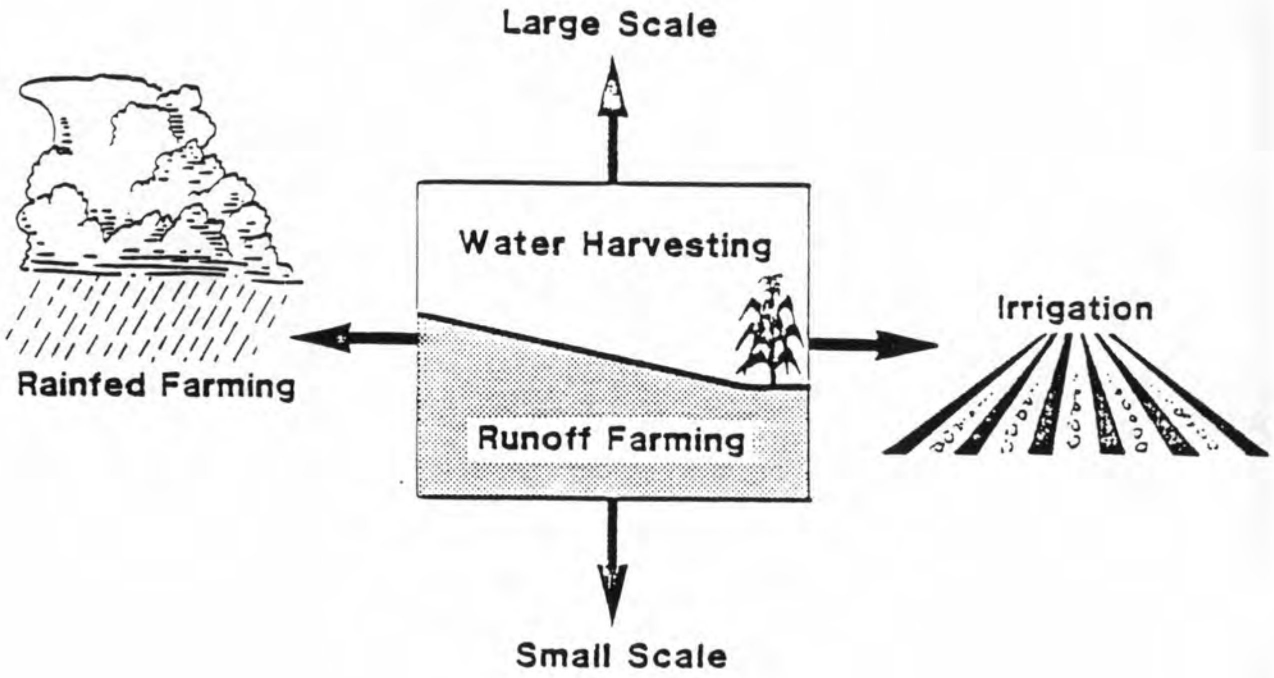
Second Edition

1986

Obtained from
Dr. Donald Slack, Agricultural and
Biosystems Engineering as reference for
ABE 550 (about 1993)

Provided by Evan Canfield, Pima County
Regional Flood Control District

Note - some pages were numbered blank pages and were not scanned.



Frontispiece. Water harvesting and runoff farming lie at an intermediate point between rainfed farming and irrigation and between large scale and small scale systems.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

PREFACE

The purposes of this primer are three-fold:

- to provide readily available information on water harvesting for crop production and runoff farming to the general public and interested professionals;
- to generalize present-day water harvesting and runoff farming technology so that it can be applied in any suitable location;
- to serve as a guide for training programs for would-be practitioners or researchers in water harvesting and runoff farming.

As indicated above, the emphasis is on water harvesting for crop production. We do not deal significantly with water harvesting for domestic or livestock supply purposes or for ground water recharge.

The material is presented in the order in which it might be used in the process of determining the applicability of water harvesting and/or runoff farming in a new location, selecting and designing an appropriate system and then constructing, operating and maintaining it. Information is given on evaluating a water harvesting or runoff farming system.

The information is written in simple English for ease in understanding by non-English speakers, and, because that is not always possible, a glossary of terms is given in Appendix B. Examples of water harvesting/runoff farming, based on University of Arizona experience at its Oracle Agricultural Center (Page Ranch) are used.

Readers of the primer who are or become actively involved in water harvesting/runoff farming research, demonstration or application will want to consult other reference materials for greater detail. Sources of information on hydrology, climatology, soils, plant sciences, engineering, economics and social sciences will be useful.

This is the second edition; it is by no means a completed effort. We have set out to be as inclusive as possible in describing the technology of water harvesting and runoff farming. Resources and time did not permit us to investigate thoroughly the activities in many countries; we had to depend on our personal knowledge or the available literature. We hope that interested people will contact us so that later editions can be made even more inclusive.

Acknowledgements

Information presented here was based on the work of many other people from around the world, their names and relevant publications are given in the references cited (Appendix A). We have drawn heavily from the pioneering work of L. Shanan and N. H. Tadmore in Israel and that of C. Brent Cluff in Arizona and other countries. We greatly appreciate their contributions to the development of water harvesting/runoff farming technology. Of particular help were other colleagues at the University of Arizona who made contributions to the manuscript and reviewed it at various states of preparation and offered helpful suggestions.

WGM
GRD
Tucson, Arizona

FOREWORD

Water Harvesting -- 2000 B.C. to 1986 A.D.

Lloyd E. Myers

The term "water harvesting" was first used by Geddes of the University of Sidney. He defined it as "the collection and storage of any farm waters, either runoff or creek flow, for irrigation use". I generalized his definition to say that "water harvesting is the practice of collecting water from an area treated to increase runoff from rainfall and snowmelt". Later, Currier defined water harvesting as "the process of collecting natural precipitation from prepared watersheds for beneficial use".

Before the development of gasoline engines and electric motors, water harvesting was a fairly common practice in a number of arid and semiarid regions. It was practiced as early as 4500 B.C. by the people of Ur and also later by the Nabateans and other peoples of the Middle East. Evenari and his colleagues described water harvesting systems in the Negev Desert, which are thought to have first been built about 4,000 years ago. By the time of the Roman Empire, these runoff farms had evolved into relatively sophisticated systems. There is evidence that less complicated systems were used about 500 years ago by ancient peoples in what is now the Mesa Verde National Park in southwestern Colorado. While the early water harvesting techniques used natural materials, such as soil crusts and rock surfaces, 20th-century technology has made it possible to use artificial means for increasing runoff from precipitation.

Collection and storage of runoff from the roofs of houses is an ancient practice that is still used in some regions. Some catchments have been built in the form of roofs without a house under them. Another significant development was the construction of roaded catchments, which were described by the Public Works Department of Western Australia. A number of catchments were built of sheet steel, concrete, and butyl rubber in the United States during the 1950's to provide water for livestock and wildlife.

In 1961, I proposed that we take an entirely different approach to the problem and investigate methods of utilizing the soil itself as the catchment structure. Early in the 1960's, research programs in water harvesting also were initiated in Israel by Hillel and at the University of Arizona by Cluff and Dutt.

Because of the intermittent nature of runoff from precipitation catchments, storage must be an integral part of any water harvesting system. When water harvesting is used for runoff farming, the storage reservoir will be the soil itself; but when the water is to be used for livestock, supplemental irrigation, or human consumption, a storage facility of some kind will have to be provided. We have made some progress in reducing seepage losses from reservoirs. We have evaluated a number of materials and methods for reducing evaporation, but our progress in reducing the cost of water storage is noticeably less than our progress in reducing the cost of water collection.

Procedures have been developed for determining the lowest cost combination of catchment size and storage size for any given combination of unit construction costs for catchment and storage, catchment efficiency, water demand schedules, and precipitation patterns. As yet, this procedure has not been utilized to determine the reliability or economic feasibility of water harvesting installations.

The quality of water obtained from catchments is not ordinarily a problem for livestock or for irrigation, but it must be considered when the water is to be consumed by humans.

When rainfall occurs just before or during the crop growing season, but is insufficient in quantity for good crop growth, water harvesting/runoff farming can be used to irrigate and produce some varieties of grain, vegetables, fruits, and nuts. Success in runoff farming depends on many factors. When trees, shrubs, and grain are grown, distribution of rainfall may not be critical. When some annual crops are grown, rain must occur at the beginning of the growing season and at regular intervals thereafter. There must also be a soil profile that can store adequate quantities of water.

A Water Harvesting Symposium was sponsored in 1974 by the U.S. Water Conservation Laboratory of the Agricultural Research Service, U.S. Department of Agriculture. A second symposium (workshop) was held in 1981, sponsored by the University of Arizona and the Chapingo Postgraduate College, Mexico. Those two events focused international attention on water harvesting for a brief period.

Twenty years ago I predicted that wide-scale application of water harvesting principles would develop within the next decade. Although a goodly number of water harvesting systems have been built, it would be difficult for me to pretend that wide-scale application has occurred. What went wrong?

We might blame the fact that some materials we thought had promise have failed the tests of field application. On the other hand, we have developed materials and methods that do reduce costs and problems of installation and that have not failed in long-term field trials under difficult conditions.

The truth is that we continue to do our research on separate components of water harvesting systems, and we report on the performance of separate components. We have not yet combined the bits and pieces of our research into useable packages for potential users. These packages must contain more information than we have developed in the past. Our potential users need much more than we have provided.

We are quite capable of developing the technical and economic information we must have before water harvesting will be adopted widely. I believe that we will do it, and on that basis I am saying once again, but with more conviction this time, that widescale application of water harvesting principles will develop by the turn of the century. There are many locations where water harvesting offers the only opportunity to develop on-site water supplies of good quality, usually at low energy costs. This source of water, based on ancient, but sound, principles clearly deserves increased attention and consideration by water resource planners and investigators.

1. INTRODUCTION

History

Water harvesting and runoff farming have been used for thousands of years in the Middle East in Egypt, Iraq, Israel, Oman, Yemen and other countries. The technique was developed hundred of years ago in the Southwest U.S. by Native Americans and is used there today. But the systems were not always successful. Why did many of these schemes fail or why were they abandoned? Some think that salt accumulated in canals and behind dams while others blame climatic change or political upheaval (Shanan and Tadmore, 1979). People always were operating their agricultural production systems at the margin of available water. In more humid regions, water harvesting or runoff farming are not needed or are not economically feasible. In more arid regions, neither water harvesting nor runoff farming may be able to make crop production possible. In simple terms, a certain level of probability of an unsuccessful crop season is part of water harvesting/runoff farming schemes because of their location on marginal lands.

Development of water resources and large scale irrigation systems in the first seven decades of this century made water harvesting and runoff farming seem to be outmoded technologies. Recent limitations in our ability to develop such large scale irrigation systems and increases in energy costs have made the outlook for water harvesting and runoff farming more favorable in certain locations.

Scientific methods of looking at water harvesting in the modern era began with the work of Richard J. Shaw and Robert R. Humphrey of the University of Arizona in the Sonora Desert of Southern Arizona and that of Michael Evenari and his associates in the Negev Desert of Israel (Humphrey and Shaw, 1957; and Evenari, et al., 1971). Their research stimulated many other scientists to re-examine the old, and in many cases dormant or forgotten, technology.

Justification

Water harvesting and runoff farming were developed to overcome moisture deficits for crop production in arid environments and/or to increase yield from existing crops or to make crop production possible where none is possible under existing conditions. They are intended to increase the probability of successful crop production on low-cost, small scale systems. About one-third of the earth's surface is arid or semi-arid land. In much of the arid land no crop production is possible because of the lack of water, and fallowing to store water for the subsequent year may not be effective because of high evapotranspiration rates (Cluff, 1981).

But there is a zone between the arid and semi-arid lands where rainfall is adequate for water harvesting/runoff farming systems. Precipitation which is wasted on non-productive areas can be recovered. Millions of hectares can be made much more productive than they are today. Population growth has forced more and more people onto these marginal lands. Improved water harvesting and runoff farming can increase people's ability to create and/or maintain a viable agricultural economy in such high risk areas.

These small scale systems make effective use of limited water supplies, take advantage of suspended organic material in flood runoff to increase soil fertility, and do not require extensive engineering design or large construction equipment. The small peak flows can be controlled with structures that are inexpensive to build and maintain (Shanan and Tadmore, 1979; Nabhan, 1979).

Definition

Water harvesting and runoff farming depend on: 1) utilizing and/or increasing runoff from rainfall on part of the land area; 2) increasing infiltration and usable soil moisture storage on the remaining land (or a part of it), and 3) making beneficial use of stored soil moisture or other "captured" water for plant growth or other uses close to the water source. Water harvesting and runoff farming do not replace traditional irrigation systems where such are possible. (See comparisons in Table 1.) The focus of water harvesting and runoff farming is on small scale systems using water near where it falls to make a high percentage of rainfall available for controlled use. Watersheds up to a few hectares in size can be from 4 to 30 times as effective in producing runoff as larger areas (Shanan and Tadmore, 1979). The technology of water harvesting and runoff farming may include spreading or diversion dikes, temporary storage and associated pumping equipment and conservation measures such as seepage control and evaporation suppression.

Water harvesting also is referred to as rain harvesting, rainfall (or precipitation) collection, and runoff collection. Runoff farming sometimes is called flood water farming or recession agriculture.

Types

Many types of water harvesting and runoff farming have evolved over the centuries - mostly on an experimental basis carried out by the farmers themselves. Three principal types can be identified as follows:

1. Water from ephemeral flows is spread in the flood plain of the stream channel itself for plant production there. Water distribution is controlled by a system of dams, dikes, and ditches (Shanan and Tadmore, 1979). Native Americans in Arizona use this method extensively.

2. Water is diverted from an existing ephemeral stream and channeled to a nearby cultivable area. Terraces and border dikes or other structures may be used to further control and distribute the flow.

3. Catchment areas are prepared or treated in some way to contribute runoff to an immediately adjacent cultivated area or storage facility.

These types are illustrated schematically in Figure 1. The first two are applied in or near ephemeral stream channels; the third is applied on a watershed, usually with no defined stream channels.

Water harvesting/runoff farming systems can be further classified according to their principal use whether for crops, forage, domestic and/or livestock water, and conservation (of soil and water). Sometimes these uses may be combined in a single system.

Crop production systems vary from the large "syrup pan" type developed in Texas for concentrating runoff on areas of up to 500 ha and applying it to

Table 1. Comparison of Irrigation and Water Harvesting/Runoff Farming

	Irrigation	Water Harvesting/ Runoff Farming
Water sources		
surface water	large rivers	small streams, washes (wadis)
ground water	high yield aquifers	not used
Water resources development		
scale	large	small
proximity to source	may be distant	always close
cost $/ha supplied	high	low
distribution system	complex, long canals	simple, short canals
storage, reservoir	common, large dams	some small reservoirs
drainage facilities	usually required	not required
Timing of application (may also involve a critical crop stress factor)	controlled	depends on individual rainfall/runoff events*
Quantity of water vs. prepared land area	usually designed to provide all of crop needs or at least a pre-season defined amount for each hectare irrigated	may not provide all of crop needs; in terrace systems only the first one may get any water in a dry year
Length of time water remains in storage	months or years	weeks or months
Equipment used in farming	much used, high technology	less used, lower level of technology

* If storage is included, timing may be partially controlled.

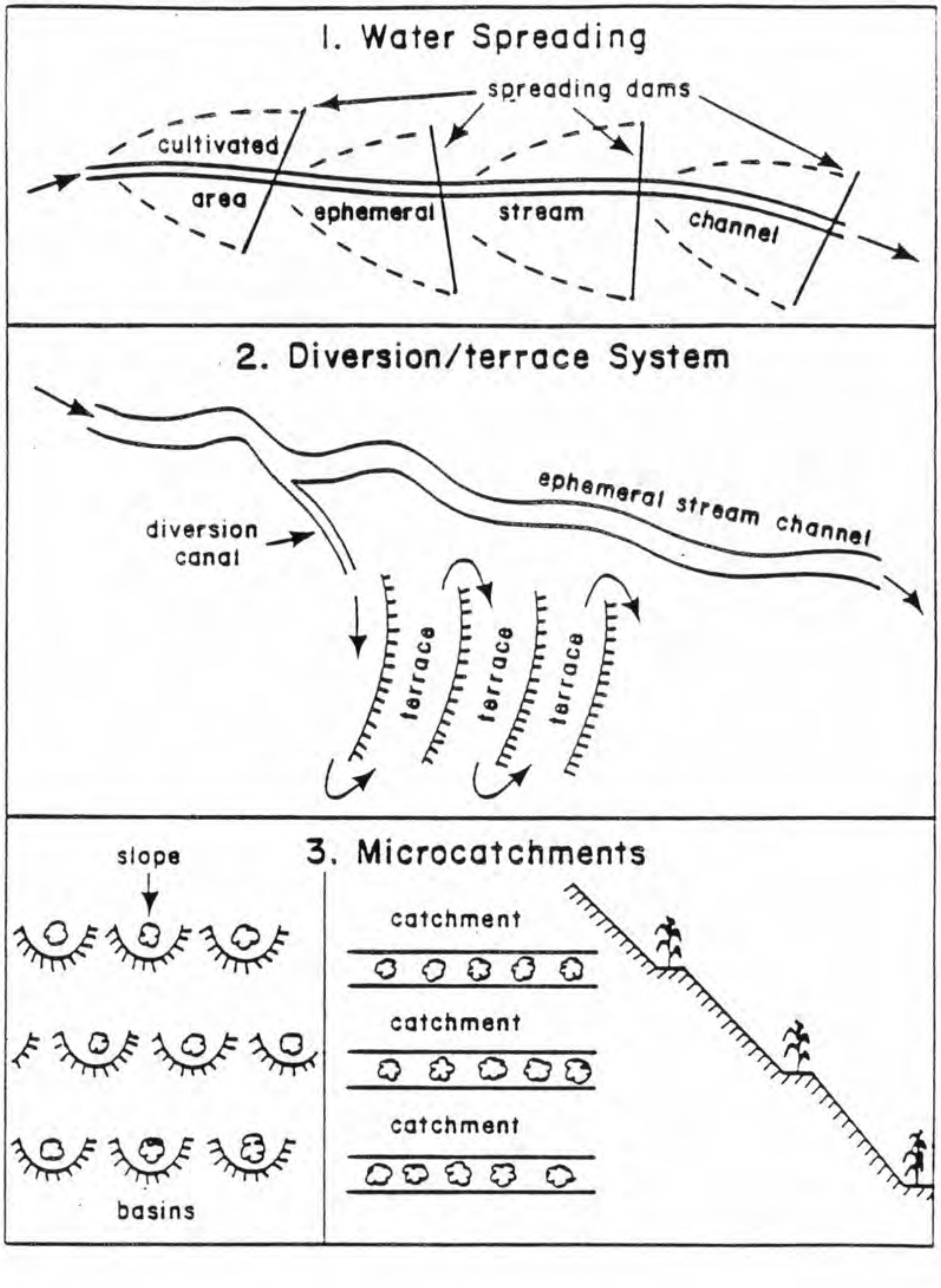


Figure 1. Types of Water Harvesting/Runoff Farming Systems

crop production on 50 ha, to small, single plant systems used by Native Americans in Arizona. There they line the depressions around individual corn plants with flat rocks to increase runoff of direct or windblown rain and get it to the plant roots. They also plant crops at the base of large sloping sandstone formations (Billy, 1981).

Recently the micro catchment concept has been promoted and developed. As the name implies, these are small scale systems which may be arranged to concentrate the runoff to a single point in small basins, also called water catchment basins or micro basins. This type is used primarily for single plant production, commonly a fruit or nut tree.

Or the arrangement may be linear, along a land surface contour. Such systems also vary in size from the modified furrows used in Mexico and Brazil to increase runoff for a single crop row to the alternating catchment area and cultivated areas wide enough for passage of agricultural machines.

Forage production systems vary from 1) the extremely small basins of pitting or land imprinting machines which usually follow a contour to 2) lister furrows or contour furrows which restrict runoff and increase infiltration at the same time to 3) contour barriers or ditches which are a form of water spreading. Zingg terraces also may be used for forage. Sometimes these methods are combined with ripping, a process which cuts deeply into the soil to remove layers which restrict infiltration.

<u>Domestic and livestock water</u> systems provide water which is of greater unit value than that for crop production. Therefore the technology used to increase, control, or store runoff can be more costly. Rain (or rainwater) traps using butyl rubber and roof (or basin roof) collection systems using sheet metal, fiberglass, asbestos cement or other roofing materials are in use. A buried membrane system is being developed in Israel for sandy soil (Shanan, et al., 1981). In Australia, diversion banks or contour drains direct runoff to waterways for rapid, low-loss movement to reservoirs. Roaded catchments are parallel ridges of steep, bare, compacted soil on a low gradient for increasing runoff and getting it into storage reservoirs. The spread bank or flat batter is a saucer shaped excavation, deeper in the center (usually in a clay subsoil) with excavated clay spread and compacted on the outside slopes for increasing runoff (Laing, 1981).

<u>Conservation systems</u> are used primarily in areas where rainfall is higher than where other types are found and where soil erosion is a major problem. The broadbed and furrow system was developed in India as an improvement of the traditional contour bunding practice to decrease erosion and conserve water for supplemental irrigation (Krantz, 1981). It involves laying out the cropping system on the watershed in a pattern which reduces furrow slope and keeps runs short. Broad beds are used for planting crops with furrows to catch excess runoff and divert it to grassed waterways (drains) where it flows into tanks. Water is then taken from the tanks for supplemental irrigation as needed (Figure 2).

All types of water harvesting/runoff farming may include actions to accomplish the following:

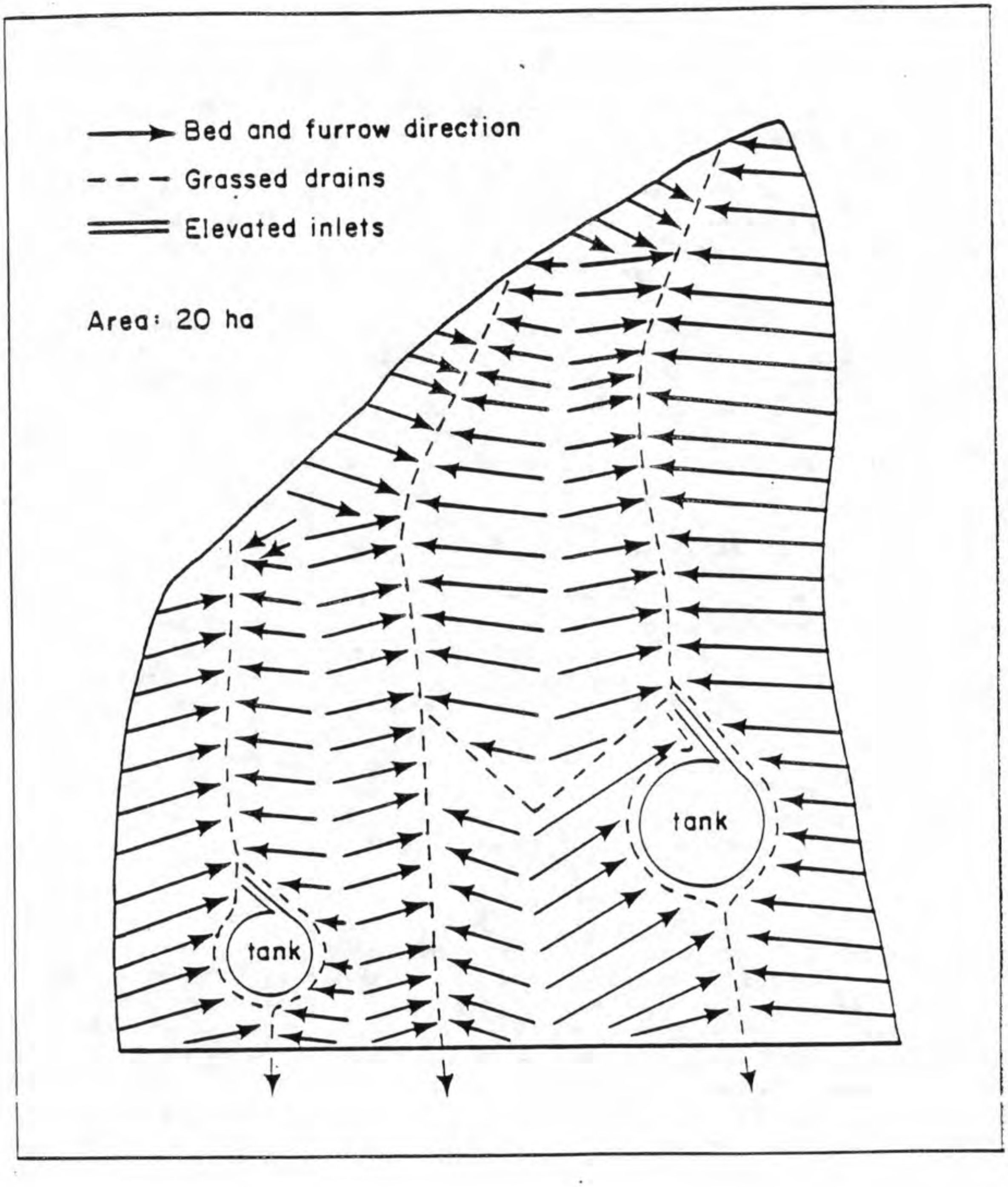


Figure 2. The graded broadbed and furrow practice of soil and water conservation and utilization. (From Krantz 1981)

Increase or control runoff (in the catchment area) by

- rock clearing
- changing or eliminating the existing vegetation, for example, from trees to grass
- land smoothing or shaping (changing slope) and construction of dikes or berms
- soil compacting
- treatment with salt (sodium) or other chemicals to disperse clays or otherwise form an impermeable layer
- adding materials such as oil, asphalt, or wax to fill soil pores and make the soil impermeable
- paving or otherwise covering the soil surface
- controlling access of humans and animals to preserve the integrity of the prepared or treated surface

Divert, convey and store water collected or diverted by

- diversion dams
- earthen or lined canals
- surface or subsurface reservoirs
- pumpback systems to return stored water to the cultivated area

Increase infiltration (in the cultivated area) by

- plowing, ripping, or otherwise loosening the soil
- soil amendments (chemical treatment) such as gypsum
- spreading dams
- mechanical devices (tubes) or sand columns to channel water into the deep root zone
- leveling or terracing to increase infiltration opportunity time
- soil modification or replacement (mixing with soil of more desirable texture and/or adding organic matter)

Storage and Pumping

When rainfall and/or runoff are uniformly distributed throughout the growing season, no reservoir storage is necessary in association with water harvesting and runoff farming systems. This is seldom the case, particularly for perennial crops.

Storage of runoff in excess of soil moisture holding capacity allows for supplemental irrigation when soil moisture is depleted. In Arizona, supplemental irrigation amounted to 18% of the water directly applied but was only 5% of that normal for grapes with irrigation and only 0.5% of that for fruit trees (Mielke and Dutt, 1981). Addition of 5 cm of supplemental irrigation doubled crop yields in India (Krantz, 1981). Pumping may be required to move the stored water from the reservoir to the cultivated area.

One additional factor supports the use of storage in water harvesting. Dikes or berms are used to keep the accumulated runoff in the cultivated areas until it all infiltrates; this may lead to crop damage from excess moisture. A lower dike or berm will avoid that problem. Then excess runoff can be stored in a nearby reservoir for application at a later date (Cluff, 1981).

Unfortunately, water stored in small reservoirs is susceptible to large losses from evaporation and seepage. Unless measures are taken to reduce such losses, the benefits of the reservoir may be negligible.

The quality of water obtained in water harvesting and runoff systems is usually adequate for livestock consumption or irrigation because it is close in time and space to its rainfall source. Where catchment areas are treated, the water must be tested to determine its suitability for domestic use. Catchment areas also may be contaminated by large or small animals (Myers, 1975). Any sediment can be removed by sediment traps. But harvested water in some cases can be an improvement over existing water supplies. Rainwater catchments had better quality water than that stored in regular earthen dams and reservoirs in Mexico (Carmona-Ruiz and Velasco-Molina, 1981). Roof runoff in Australia was of excellent quality for kitchen use without treatment--provided roofs and gutters were kept clean, and the storage tank couldn't be contaminated (Laing, 1981).

Water Management

Water harvesting/runoff farming systems are methods of small-scale water management. Figure 3 is a flow diagram showing in general terms how water moves through such systems from its source as rainfall to its consumptive use by crops or to its loss from the systems by evaporation, deep percolation, or runoff. Various ways in which the components of the systems can be managed by people for crop production are described in the remaining chapters of this book.

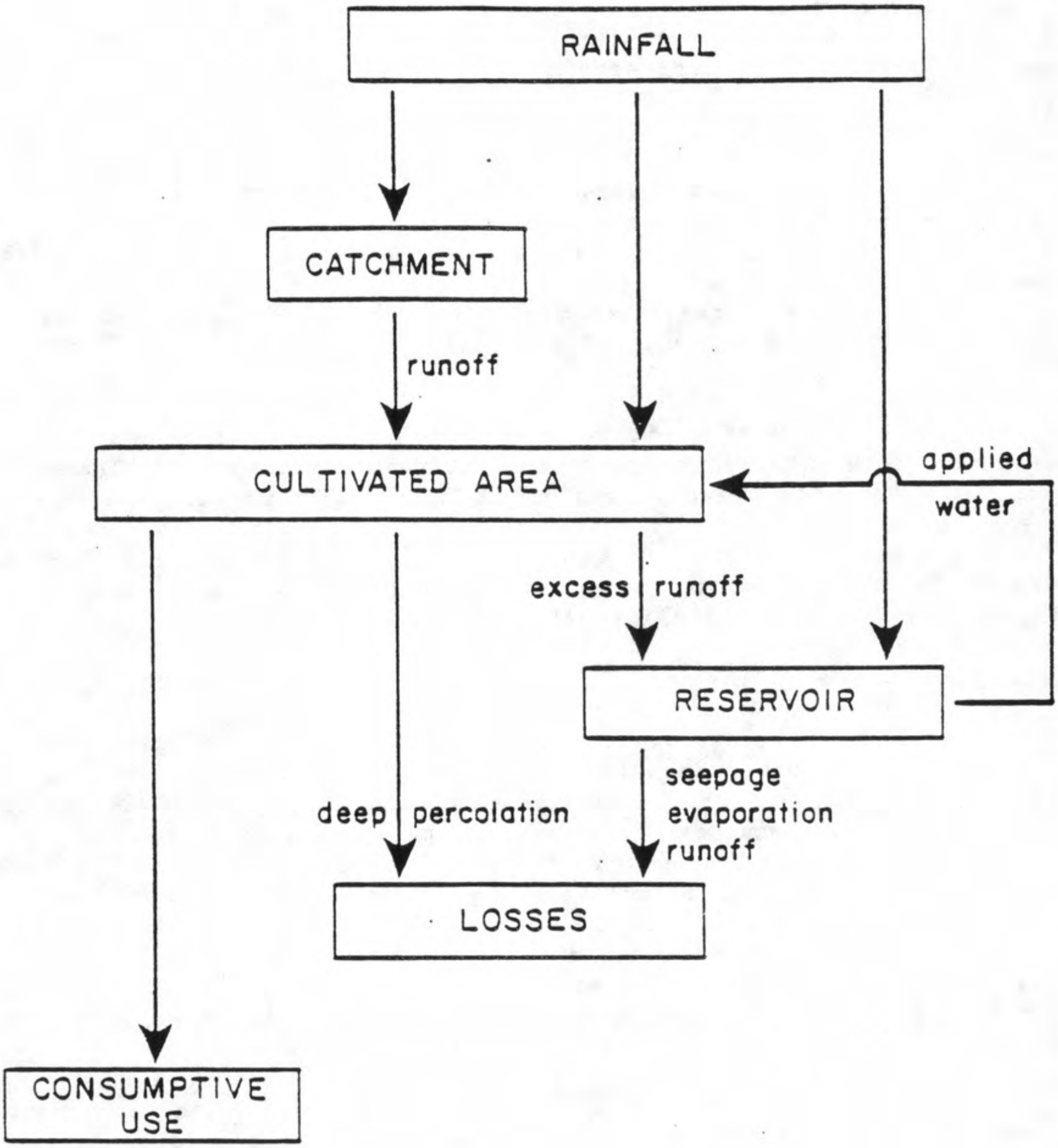


Figure 3. Flow diagram for water harvesting/runoff farming systems.

2. DESIGN FACTORS

Design of water harvesting/runoff farming systems depends on knowledge of many factors about the specific area in which the systems will be used. In only a few cases will all of the factors discussed below be defined adequately prior to starting construction of the system. Obviously, the better the initial knowledge is, the fewer are the future adaptations and modifications which will be required to make the installed system operate properly. Where actual measurements of these factors are not available, as is frequently the case, discussions with long-time residents of the area, if any can be found, may prove useful in making estimates.

Climate (General)

Beginning and ending dates of the growing season, and number of frost free days will determine what types of crops can be grown in those areas which have a cold season. Several years of data are needed to determine the average frost free period. Selection of crops will be limited further by the maximum and minimum temperatures which may occur and the range of wind velocities. Climatic data for the Oracle Agricultural Center (OAC) near Tucson, Arizona are given in Table 2.

In the absence of specific information on crop water requirements, described in a later section, potential evapotranspiration (ET) can be used to determine what the overall moisture deficit is during the growing season, i.e.g, how much moisture must be supplied by the water harvesting/runoff farming system. A potential ET curve can be computed for many locations from basic climatic data using procedures developed by various investigators. (See Figure 4 and Thornthwaite and Mather, 1957, for example.)

Rainfall

Total annual rainfall, its distribution in time and space, and its probabilities of occurrence in the particular location (probable number of days or weeks with rainfall greater than a certain amount) will be used in determining what crops can be grown and the size of water harvesting system for a given cultivated area. There is no absolute minimum or maximum level of annual rainfall for successful water harvesting systems. Most researchers feel that 250-350 mm is near the minimum from a water supply standpoint, and few water harvesting systems are found in areas of greater than 750 mm annual rainfall, probably because of economic considerations. Water harvesting/runoff farming systems may be economically feasible in areas of greater rainfall if it falls in a single, short season.

If rainfall data are unavailable for the specific location, records of nearby stations, if any, may be used for estimating rainfall. If rainfall occurs in more than one season, the season of lowest rainfall probably is the one for which design criteria will have to be established.

In arid and semi-arid areas there are long periods of each year without rain. Knowledge of the length of these expected dry periods is used in determining whether storage will be required for perennial crops.

Table 2. Climatic Data for Oracle Agricultural Center

Month	First and last frosts* average (date)	Temperatures			Wind**	
		Mean Maximum (^{o}C)	Mean Minimum (^{o}C)	Mean (^{o}C)	Maximum (km/hr)	Average (km/hr)
JAN		15.06	2.94	9.00	43	9.3
FEB		15.72	3.56	9.61	48	9.7
MAR	13 (last)	19.61	5.89	12.72	53	10.5
APR		22.94	7.11	15.00	55	10.9
MAY		29.17	12.72	20.94	48	10.6
JUN		35.11	18.61	26.83	47	10.6
JUL		35.61	21.44	28.50	76	10.5
AUG		33.94	19.83	26.89	71	9.5
SEP		32.39	18.00	25.17	56	9.8
OCT		26.67	11.94	19.28	47	10.0
NOV	30 (first)	20.00	7.00	13.50	47	10.0
DEC		15.06	2.72	8.89	47	8.9

* average length of growing season - 262 days

** University of Arizona - Tucson

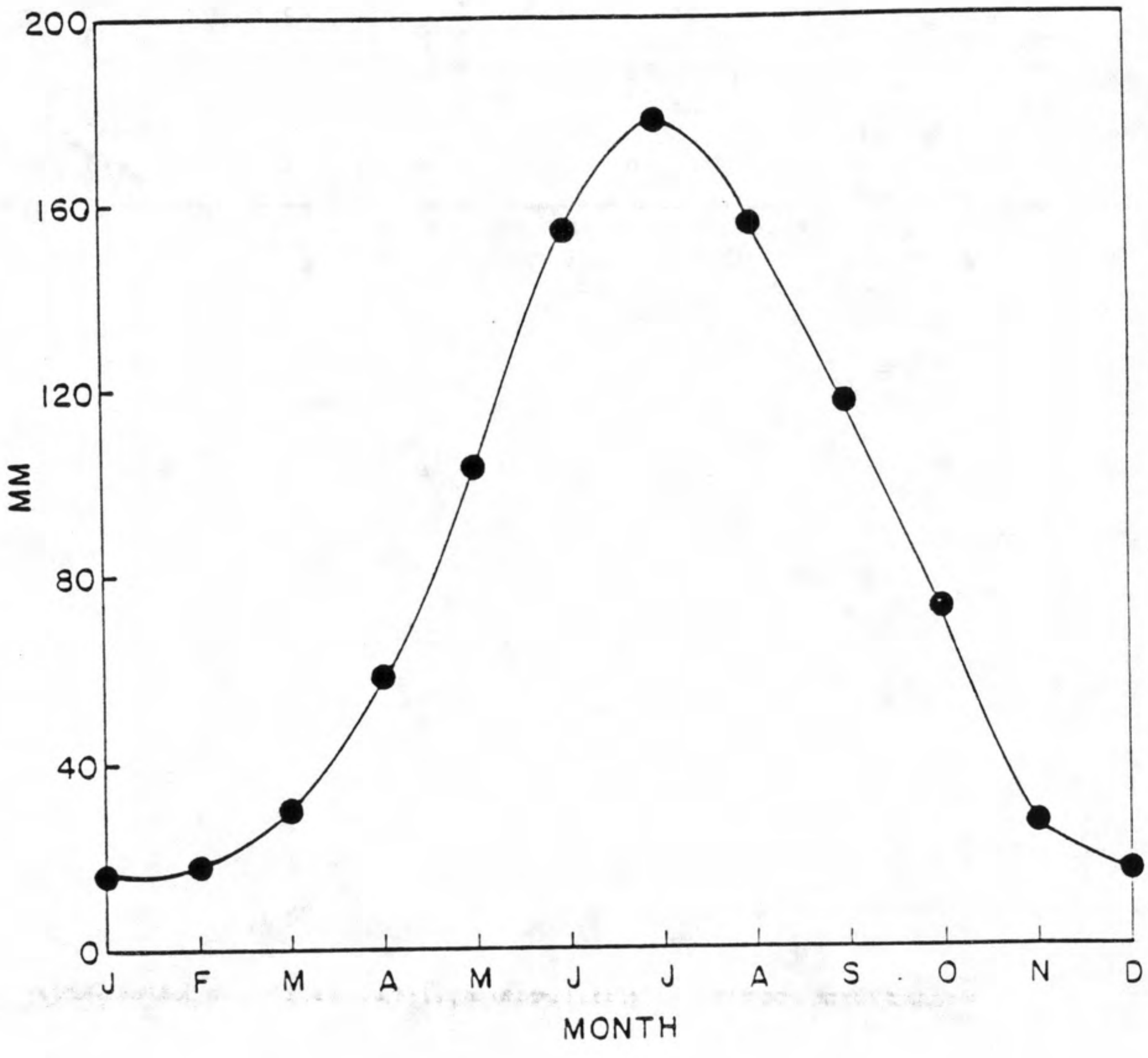


Figure 4. Potential Evapotranspiration at the Oracle Agricultural Center in Southern Arizona.

24

The relation of rainfall to runoff under natural or existing conditions and rainfall intensity data will assist in determining what treatment may be applied to the catchment area and what its dimensions should be for micro catchment systems. The relation of rainfall to crop water requirements will determine which crops can be grown and how big the water harvesting system must be.

Rainfall records are based on periodic measurements, usually made daily, but sometimes only weekly or even monthly. More frequent measurements are more useful in predicting hydrologic events. The periodic data then are used to determine averages and probability of occurrence for various events or levels of rainfall. Daily rainfall data permit detailed statistical analyses, determination of probability, and modeling studies. Weekly or monthly data will result in less accurate computations, and annual data alone will allow only gross comparisons and analyses. A description of the procedure for determining probabilities of hydrologic events can be found in statistics texts or handbooks (Linsley, et al, 1982). A 10-year rainfall record is adequate, but with such a short record extremely high years should be eliminated from the analysis.

Daily rainfall records were used to determine average weekly rainfall and rainfall with 50 percent probability of occurrence for the Oracle Agricultural Center in Southern Arizona (Matias, 1983). (Figure 5). These data will be used later in computations for an example water harvesting system.

Daily rainfall amounts also are used for calculating runoff from small watersheds and micro catchments. Shanan and Tadmor (1979) determined the mean number of rainy days according to rainfall depth in the Negev Highland area (Table 3). A similar analysis for OAC is included in the table.

Storm frequency and intensity are also important factors in determining runoff with some equations. They are useful in estimating erosion. Shanan and Tadmor (1979) suggest that rainfall intensities with return period frequencies of 2, 5, and 10 years are needed for micro catchment design. Examples of their rainfall intensity curves, typical of the Negev, are given in Figure 6. Superimposed are simmilar data for OAC.

Runoff

Extensive research has been done in estimating runoff, but most methods have been derived from observations on large watersheds and have limited application to small catchments. Watershed conditions are never uniform, and small areas include different slopes, soil types, vegetation and other surface cover. All these factors affect the runoff potential of a site.

Watersheds require a threshold rainfall before runoff begins. In the Negev desert in Israel, for example, watersheds larger than a few square kilometers in size require a threshold rainfall of 8 to 12 mm while micro catchments produce runoff with a threshold of only 2 to 3 mm (Shanan and Tadmor, 1979).

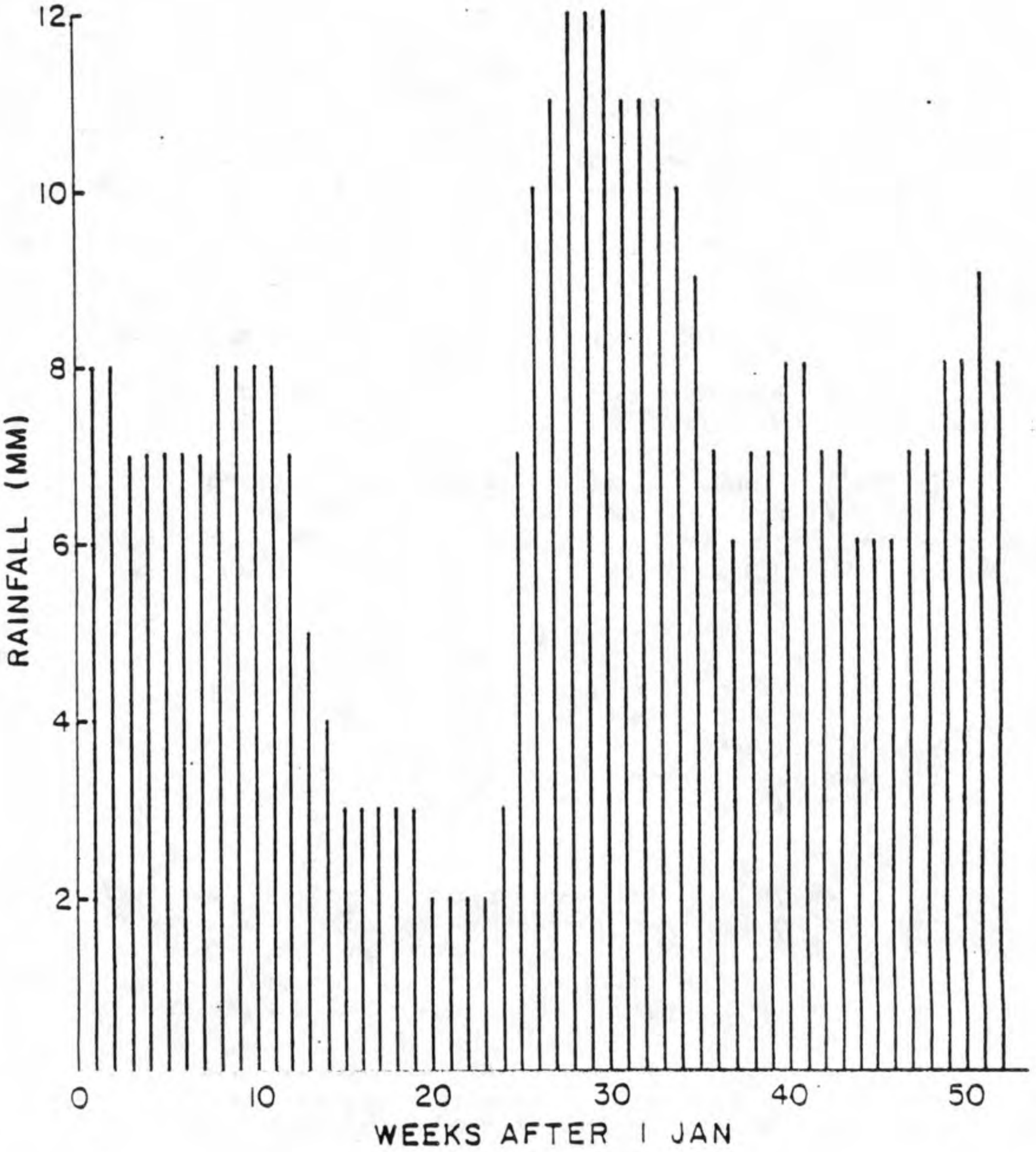


Figure 5. Rainfall with 50 Percent Probability of Occurrence for OAC
Source: Matias, 1983.

Table 3. Average Number of Rainy Days Per Year of Various Rainfall Depths

Rainfall depth (mm)	No. of rainy days per year	
	Negev Highland (100 mm total)	OAC* (360 mm total)
0 - 5		15
1.0 - 2.9	12	
3.0 - 5.9	7	
5.0 - 10.0		7
6.0 - 8.9	5	
9.0 - 19.9	3	
10.0 - 20.0		7
Greater than 20.0	1	5

* Oracle Agricultural Center (Page Ranch)

Sources: Shanan and Tadmor, 1979; Matias, 1983.

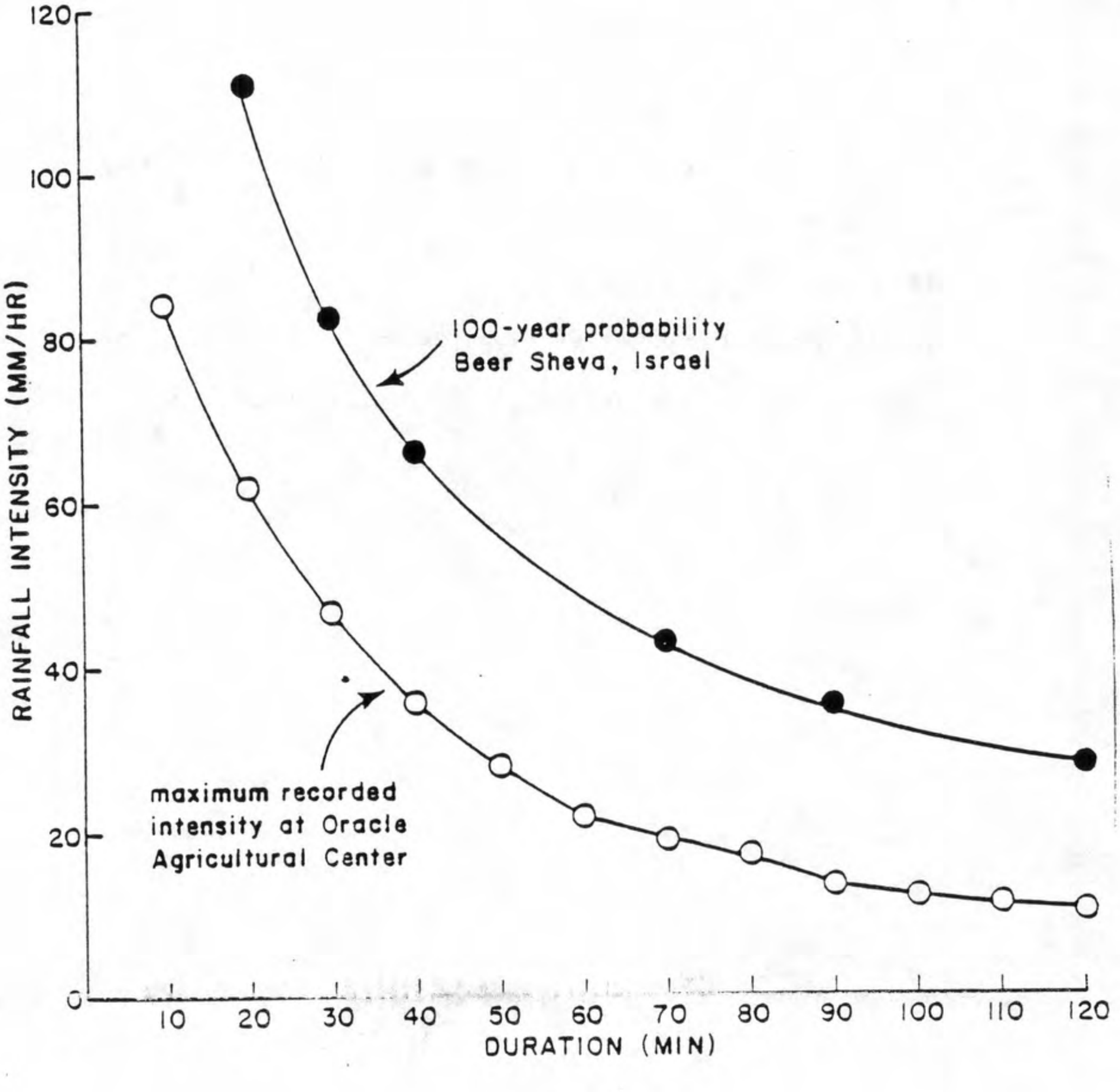


Figure 6. Rainfall Intensity vs. Duration. (Data for the Negev Desert of Israel from Shanan and Tadmor, 1979).

Equations of the types

runoff = constant a (rainfall - constant b) x watershed area

where the constant b is called threshold rainfall (mm)

or

runoff = constant a x rainfall intensity x watershed area

where constant a is a percent

must be derived if not already known, to be able to calculate size of diversion dams, canals, and terraces, spacing and size of spreading dams and catchment areas.

Watershed models have been developed for many areas in the U.S. and some other countries. They may be useful in other areas where climatic conditions are not too dissimilar and where any simplifying assumptions used in their formulation are valid.

Small Watersheds

There are many methods to predict runoff on small, semiarid watersheds. In this section we describe one method used by Lane (1982a, 1982b) to predict runoff from such areas and a method to predict streamflow in ephemeral stream channels. The descriptions apply to watersheds from 1 to 1000 ha (approximately) where precipitation is dominated by rainfall, and stream channels are ephemeral. Individual rainfall-runoff events are important, not base flow or snow melt, and surface runoff is the only component. Runoff volume and peak rate are examined and hydrograph approximations are made.

Figure 7 is a definition sketch for runoff from small areas with a subwatershed divided into upland and lateral components. Figure 8 shows a general relationship between rainfall and infiltration. Infiltration is the process whereby water enters the soil surface. The maximum rate at which water percolates through the soil surface is called "infiltration capacity". Runoff occurs when rainfall intensity exceeds infiltration capacity. The actual process is shown in the upper half of the figure; a first approximation appears below. The approximate relationships are defined by the following equations:

total rainfall: $P = \int_{0}^{T} p(t)\,dt$ (mm)

initial abstractions: $Ia = \int_{0}^{t^1} p(t)\,dt$ (mm)

infiltration volume: $F^1 = \int_{t_1}^{t^2} f(t)\,dt + \int_{t_2}^{T} p(t)\,dt$ (mm)

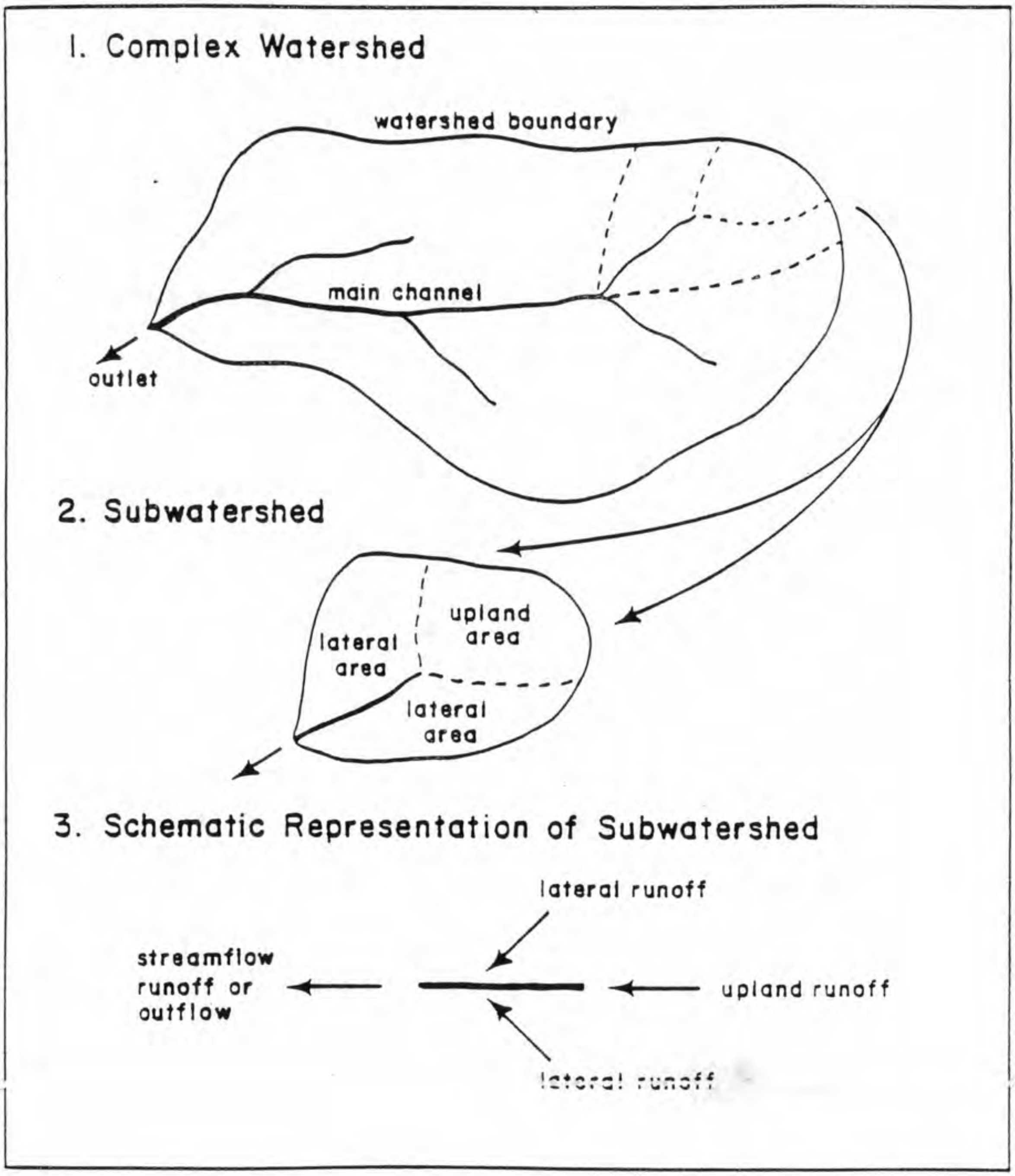


Figure 7. Definition Sketch for Runoff Computation
Source: L. Lane, 1982b

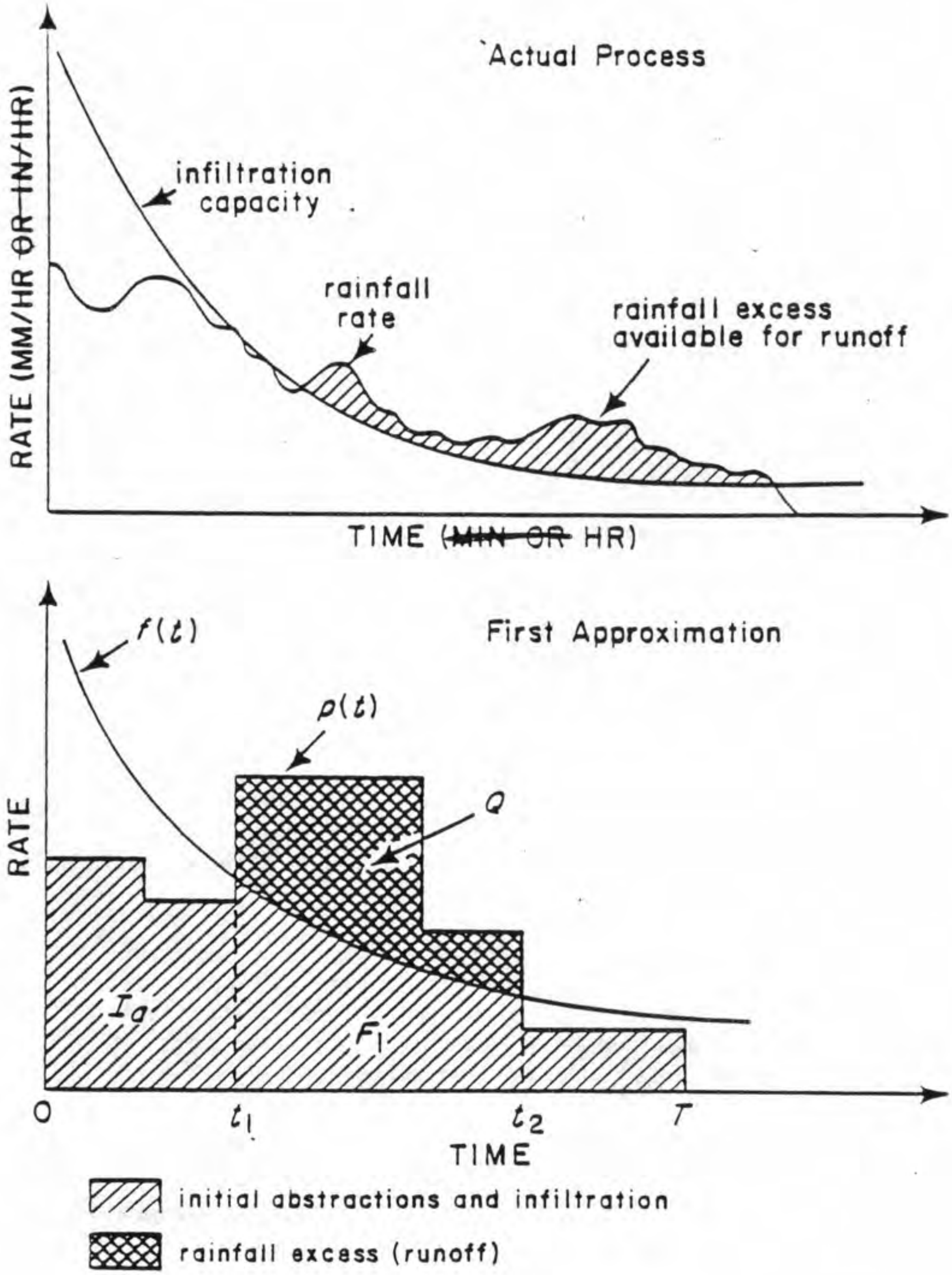


Figure 8. Relationship Between Rainfall and Infiltration
Source: L. Lane, 1982b

total losses: $F = Ia + F'$ (mm)

runoff volume: $Q = P - F = P - Ia - F'$ (mm)

calculating runoff:

$$Q = \begin{cases} 0.0 & \text{if } P < \text{or} = Ia \\ P - F & P > Ia \quad \text{(mm)} \end{cases} \qquad (1)$$

Equation (1) is a general runoff equation. The USDA/SCS equation below for daily rainfall and runoff can be used as an approximation of equation (1) (Soil Conservation Service, 1972).

$$Q = \begin{cases} 0.0 & \text{if } P < \text{or} = 0.2S \\ (P - 0.2S)^2/(P + 0.8/S) & P > 0.2S \end{cases} \qquad (2)$$

Q = runoff (as depth over watershed) (mm)

P = total rainfall (mm)

S = retention parameter (mm)

0.2S = initial abstractions (mm)

The runoff curve number, (CN), is defined as:

$CN = 25{,}400/(254 + S)$ (S in mm)

Runoff curve numbers are given in Table 4 for different soils and soil cover. Hydrologic soil groups are described in Tables 5 and 6. The retention parameter, S, can be calculated for a given curve number selected from the tables as:

$S = (25{,}400/CN) - 254$ (mm)

Equation (2) is then used to calculate the runoff resulting from a given rainfall event.

The double-triangle hydrograph method is a procedure to approximate the shape of a runoff hydrograph and from that, the peak discharge. Figure 9 is a schematic illustration of the double-triangle hydrograph. The upper postion of the figure is an actual hydrograph. The lower portion shows the same hydrograph approximated by two triangles.

The approximate relationships for hydrographs on small semiarid watersheds are given by equations (3), (4), and (5).

a. The mean duration of flow, $\bar{D}$, in hours is:

$$\bar{D} = C_1(2.59A)^{C_2}$$

where

$\bar{D}$ = mean duration of flow (hours)

A = watershed area (km^2)

Table 4. Runoff curve numbers for hydrologic soil-cover complexes

(Antecedent moisture condition II, and $I_a = 0.2S$)

Cover			Hydrologic soil group			
Land use	Treatment or practice	Hydrologic Condition	A	B	C	D
Fallow	Straight row	----	77	86	91	94
Row crops	"	Poor	72	81	88	91
	"	Good	67	78	85	89
	Contoured	Poor	70	79	84	88
	"	Good	65	75	82	86
	Contoured and terraced	Poor	66	74	80	82
	Contoured and terraced	Good	62	71	78	81
Small grain	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Contoured	Poor	63	74	82	85
		Good	61	73	81	84
	Contoured and terraced	Poor	61	72	79	82
		Good	59	70	78	81
Close-seeded legumes[1] or rotation meadow	Straight row	Poor	66	77	85	89
	"	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	"	Good	55	69	78	83
	Contoured and terraced	Poor	63	73	80	83
	Contoured and terraced	Good	51	67	76	80
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	"	Fair	25	59	75	83
	"	Good	6	35	70	79
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads		----	59	74	82	86
Roads (dirt)[2]		----	72	82	87	89
(hard surface)[2]		----	74	84	90	92

---

[1] Close-drilled or broadcast

[2] Including right-of-way

Source: Soil Conservation Service, 1972

Table 5. Soils descriptions and hydrologic soil groups

Soil Group	Characteristics	Comments
A.	Soils with high infiltration rates, even when wetted. Well to very well drained gravel, sand, loamy sands, and sandy loam. Soils with depths of 100 cm or greater without infiltration-reducing layers.	Soils with low runoff potential and low runoff curve number.
B.	Soils with moderate infiltration rates. Moderately well to well drained soils with moderately fine to moderately coarse texture. Usually moderately deep soils (50 cm or more).	Low to moderate runoff potential and runoff curve numbers.
C.	Soils with slow infiltration rates. Soils with moderately fine to fine texture, or with an infiltration-reducing layer. Usually less than 50 cm of soil over an infiltration-impeding layer.	Moderate to high runoff potential and runoff curve numbers.
D.	Soils with very slow infiltration rates. Clay soils with swelling potential, shallow soils over a clay layer, and shallow soils over nearly impervious material. Usually less than 30 cm of soil over an infiltration-restricting layer.	Soils with high runoff potential and high runoff curve numbers.

(Source: Soil Conservation Service, 1972; metric conversion by authors)

Table 6. Hydrologic soil-cover complexes and associated runoff curve numbers

Cover type, density, or condition	Runoff curve numbers by hydrologic soil group			
	A	B	C	D
Bare soil and impervious areas:				
Unimproved bare soil:	72	82	87	90
Hard surface dirt roads	74	84	90	92
Exposed bare rock	96	96	96	96
Completely impervious urban areas	99	99	99	99
Desert brush:				
< 10% cover	--	84	88	93
< 20% cover	--	83	87	92
< 40% cover	--	82	86	90
Pasture or range:				
Poor	68	79	86	89
Fair	49	69	79	84
Good	39	61	74	80
Herbaceous, brush and grass:				
20% cover	--	79	86	92
40% cover	--	74	82	90
60% cover	--	69	77	88
Pinon-Juniper-grass:				
40% cover	--	65	75	88
60% cover	--	57	70	86
80% cover	--	48	62	83
Ponderosa pine:				
40% cover	--	61	75	80
60% cover	--	55	70	77
80% cover	--	49	65	73

Sources: Soil Conservation Service, 1972; Zeller, 1979; Branson, et al., 1981

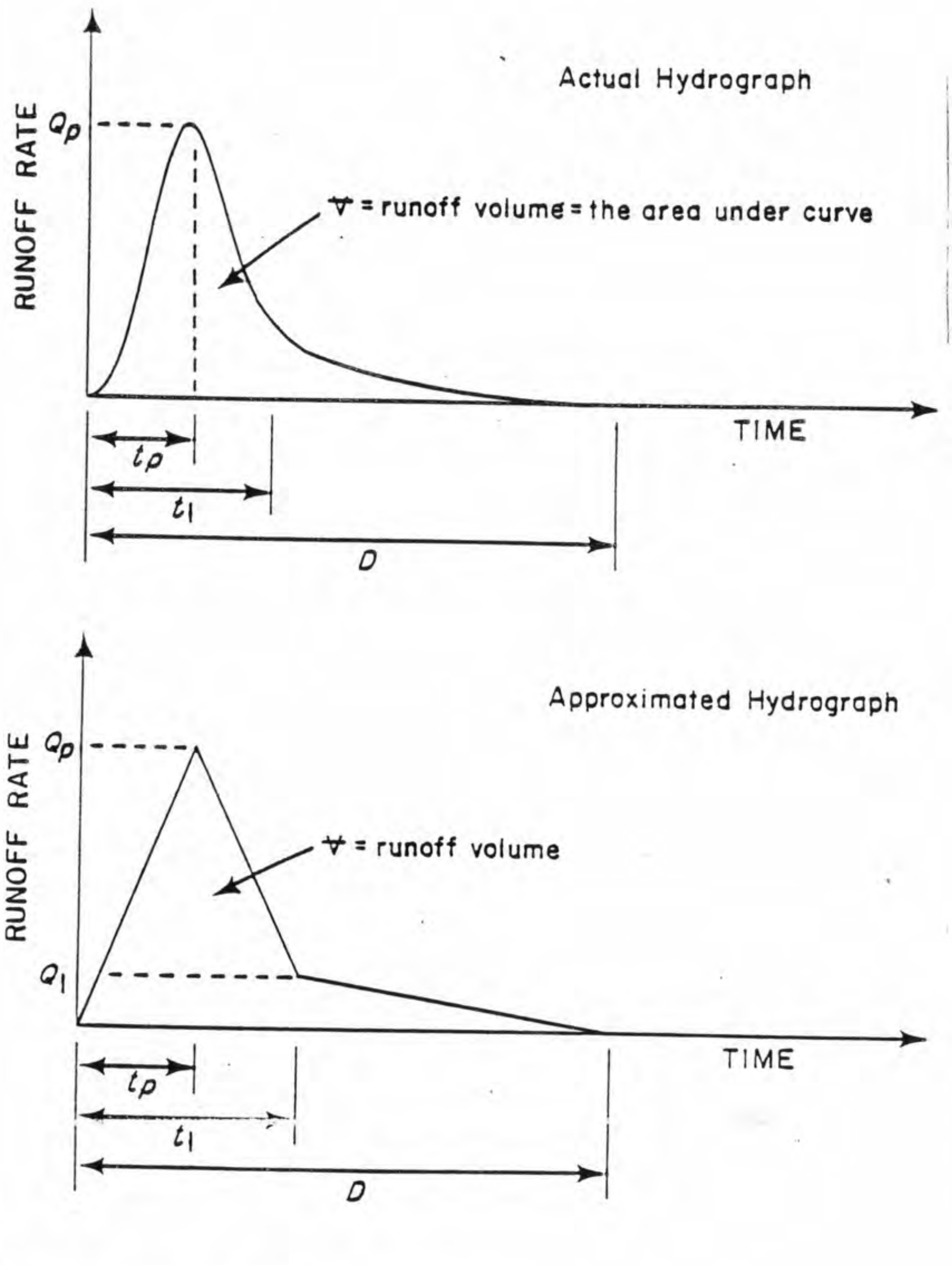


Figure 9. Schematic of Double Triangle Hydrograph
(Source: L. Lane, 1982b)

C_1, C_2 = parameters

The parameter values in Equation (3) are:

Coefficient C_1:

1. $CN < 70$	$4.5 < C_1 < 5.5$
2. $70 < CN < 80$	$3.5 < C_1 < 4.5$
3. $CN > 80$	$2.0 < C_1 < 3.5$

Exponent C_2:

C_2 is approximately equal to 0.2

b. The mean runoff volume per event, V, is:

$$V = 25.4\ C_3\ (2.59A)^{C_4}$$

where

V = mean volume of runoff (mm)

A = watershed area (km^2)

C_3, C_4 = parameters

The parameter values in Equation (4) are:

Coefficient C_3:

1. $CN < 70$	$0.03 < C_3 < 0.04$
2. $70 < CN < 80$	$0.04 < C_3 < 0.05$
3. $CN > 80$	$0.05 < C_3 < 0.10$

Exponent C_4

C_4 is approximately equal to -0.2

c. The peak discharge relationship is:

$$Q = C_5V/D \qquad (5)$$

where

Q = peak discharge (mm/hr),

V = runoff volume (mm),

D = duration of flow (hrs)

C_5 = parameter

The parameter values in Equation (5) are:

Coefficient C_5:

1. Slope of main channel, $Sc < 0.01$
    - a. $CN < 70$ $\quad 2.8 < C_5 < 3.0$
    - b. $70 < CN < 80$ $\quad 3.0 < C_5 < 3.5$
    - c. $CN > 80$ $\quad 3.5 < C_5 < 4.0$
2. Slope of main channel, $Sc > 0.01$
    - a. $CN < 70$ $\quad 3.5 < C_5 < 4.0$
    - b. $70 < CN < 80$ $\quad 4.0 < C_5 < 5.0$
    - c. $CN > 80$ $\quad 4.5 < C_5 < 6.0$

The procedure to estimate runoff volume, duration of flow, and peak discharge can be summarized as follows:

<u>Given</u>: Watershed area, A, and slope of main channel, Sc
runoff curve number, CN (from tables)
depth of rainfall, P

a. Compute S

$$S = 25{,}400/CN - 254$$

b. Compute runoff volume Q = V

$$Q = V = \begin{cases} 0.0 & P < \text{or} = 0.2S \\ (P - 0.2S)^2/(P + 0.8S) & P > 0.2S \end{cases} \qquad (2)$$

c. Compute mean duration of flow

$$\bar{D} = C_1(2.59A)^{C_2} \qquad (3)$$

d. Compute peak discharge

$$Qp = C_5 \; V/\bar{D} \qquad (5)$$

The standard double-triangle hydrograph approximation is made as follows:

Let: $t_p = 0.2D$

$t_1 = 0.4\ D,$

$Q_1 = 0.2\ Q_p$

Given: $\bar{V}$ from Equation (2)

D from Equation (3)

Q_p from Equation (5)

Compute equivalent duration D. Note $D = \bar{D}$

$$D = (25/7)\ \bar{V}/Q_p = (25/7)\ \bar{D}/C_5 \tag{6}$$

The approximate hydrograph is then:

$$Q(t) = \begin{cases} (Q_p/tp)\ t & \text{if} \quad 0 < \text{or} = t < \text{or} = tp \\ (9/5)\ QP - (4/5)\ (QP/tP)\ t & tp < t < \text{or} = 2tp \\ (1/3)\ QP - (1/15)\ (QP/tp)\ t & 2tp < t < \text{or} = D \end{cases}$$

where

$$tp = 0.2D$$

$$D = (25/7)\ \bar{D}/C_5$$

<u>Transmission Losses</u>. Runoff in ephemeral streams is subject to infiltration into the channel bed and banks. Infiltration losses are called transmission losses because runoff volumes and peak rates may be reduced as they are transmitted down the channels. This is illustrated in Figure 10.

The differential equation describing transmission losses for the channel reach shown in Figure 11 is as follows:

$$d\bar{V}/dx = -wc - wk\ \bar{V}(x,w) + \bar{V}lat/x \tag{8}$$

with solution

$$\bar{V}(x,w) = (-c/k)\ (1-e^{-kxw}) + e^{-kxw}\ (\bar{V}up) + (1-e^{-kxw})/kxw\bar{V}lat \tag{9}$$

let:

$$a(x,w) = (-c/k)\ (1-e^{-kxw}) = [a/(1-b)][1-b(x,w)] \tag{10}$$

$$b(x,w) = e^{-kxw} \tag{11}$$

$$F(x,w) = (1-e^{-kxw})/kw = [1-b(x,w)]/kw \tag{12}$$

$$b = e^{-k} \tag{13}$$

Then equation 9 becomes

$$\bar{V}\ (x,w) = a(x,w) + b(x,w)\bar{V}up + F(x,w)\ \bar{V}lat/x \tag{14}$$

when $\bar{V}(x,w) > 0$.

39

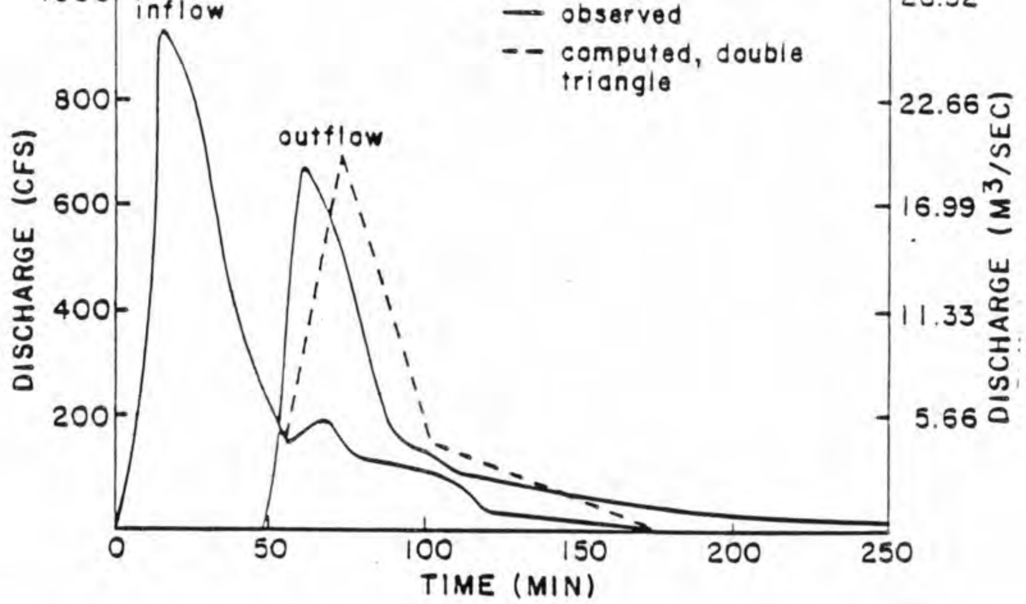


Figure 10. Inflow-outflow Hydrographs for Walnut Gulch Watershed in Southern Arizona

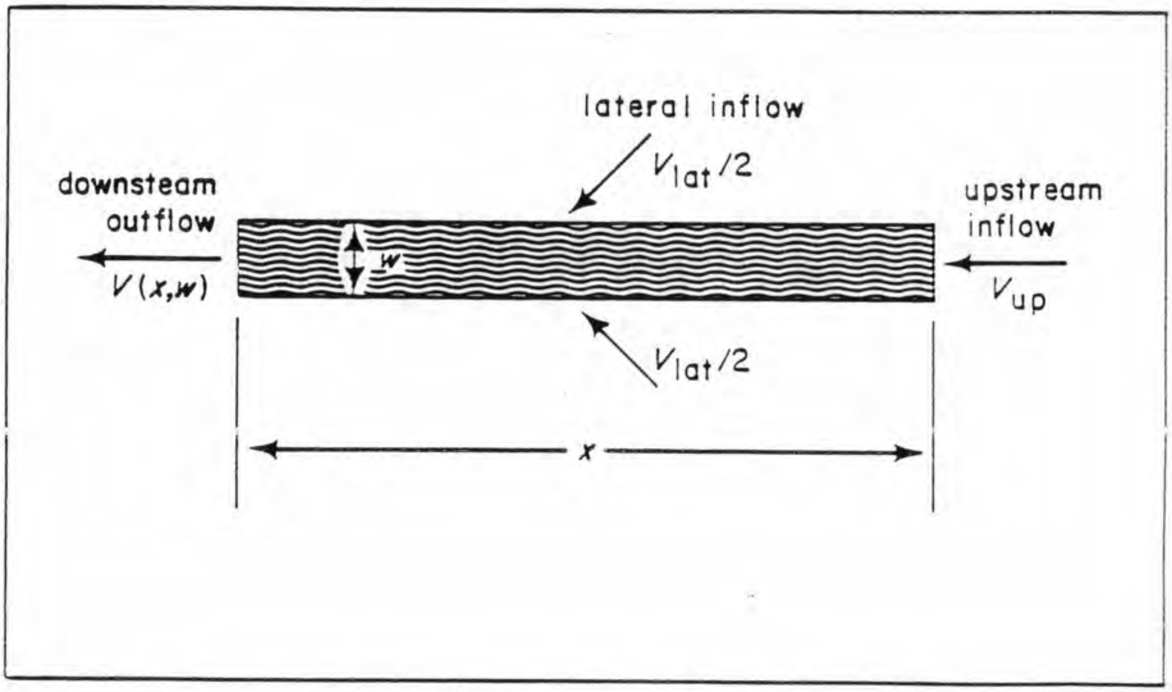


Figure 11. Illustration of Theoretical Channel Reach

Set V_{lat} and $V(x,w)$ in Equation 14 to zero and solve for the threshold inflow. Inflow volumes (without lateral inflow) less than the threshold are all lost so the outflow is zero. The threshold is

$$Po = -[a(x,w)]/[b(x,w)] \tag{15}$$

with this threshold, the transmission loss equation is

$$V(x,w) = \begin{cases} 0.0 & \text{if } V(x,w) < \text{ or } = 0.0 \\ a(x,w) + b(x,w)Vup + F(x,w)\ Vlat/x & V(x,w) > 0.0 \end{cases} \tag{16}$$

If we know a and k, Equations (10) - (13) can be used to determine parameters a(x,w), b(x,w), F(x,w), and Po in Equations (15) and (16).

Case 1: Observed inflow-outflow data are available.

Step 1: Select runoff events where $Vlat = 0.0$

Step 2: Derive estimates of a(x,w) and b(x,w) using regression analysis. (statistical process)

Step 3: Calculate k, b, and a as follows

$$b(x,w) = e^{-kxw}$$

$$-kxw = \ln b(x,w)$$

$$k = (-1/xw) \ln b(x,w)$$

$$b = e^{-k}$$

$$a = [(1-b)\ a(x,w)]/[1-b(x,w)]$$

then, $F(x,w) = [1 - b(x,w)]/kw$

Case 2: No observed inflow-outflow data are available.

Lane (1980) derived estimates of a and k as follows:

$$a = -0.00465\ K\ \bar{D} \tag{17}$$

$$k = -1.09 \ln [1.0 - 0.00545\ K\ \bar{D}/\bar{V} \tag{18}$$

where

K = effective hydraulic conductivity of the channel alluvium (mm/hr)

$\bar{D}$ = mean duration of flow (hours) calculated from Equation (3)

$$\bar{D} = C_1(2.59A)^{C_2}$$

$\bar{V}$ = mean runoff volume in 1000 m^3 calculated from Equation (4)

$$V = 25.4\ C_3\ (2.59A)^{C_2} \text{ x watershed area (ha)/100}$$

Now, given a and k from Equations (17) and (18) calculate the parameters as follows:

$$b = e^{-k} \tag{19}$$

$$b(x,w) = e^{-kxw} \tag{20}$$

$$a(x,w) = [a/(1-b)]\ [1-e^{-kxw}] \tag{21}$$

$$F(x,w) = (1/kw)\ [1 - e^{-kxw}] \tag{22}$$

Values of effective hydraulic conductivity for various bed materials are shown in Table 7.

For a given channel reach the procedure is as follows:

Step 1. - Estimate upland and lateral inflows

1. Use Equation (2) to estimate Vup and Vlat in mm.
2. Convert Vup and Vlat to 1000 m^3 (multiply by area of watershed, ha/100)

Step 2. - Estimate transmission loss equation parameters

1. Estimate K from Table 7
2. Estimate $\bar{D}$ from Equation (3)
3. Estimate V from Equation (4) and convert to 1000 m^3
4. Estimate a from Equation (17) and k from Equation (18)
5. Estimate b, b(x,w), a(x,w), and f(x,w) from Equations (19)-(22)

Step 3. - Compute outflow volume

1. Compute Po from Equation (15)
2. Compute V(x,w) from Equation (16) and convert to mm

Step 4. - Compute peak discharge of the flow

1. Estimate C_5
2. Compute QP using Equation (5) and V(x,w) in mm

Step 5. - Estimate the outflow hydrograph

1. Compute D using Equation (6)
2. Compute the hydrograph using Equation (7)

Table 7. Effective hydraulic conductivity for transmission losses in channel alluvium[a]

Bed Material Group (1)	Bed Material Characteristics (2)	Effective Hydraulic Conductivity[b] (mm/hr) (3)
1 Very high loss rate	Very clean gravel and large sand. $d_{50} > 2$ mm	> 125
2 High loss rate	Clean sand and gravel under field conditions. $d_{50} > 2$ mm	50 - 125
3 Moderately high loss rate	Sand and gravel mixture, with less than a few percent silt-clay	25 - 75
4 Moderate loss rate	Mixture of sand and gravel, with significant amounts of silt-clay	6 - 25
5 Very low loss rate	Consolidated bed material with high silt-clay content	0.025-2.5

---

[a] Based on analysis of data from 14 channel reaches in Arizona, Texas, Kansas, and Nebraska, data from 14 other channel reaches in Arizona, and canal seepage rates in unlined canals (Lane, 1980).

[b] Values of effective hydraulic conductivity reflect the flashy, sediment-laden character of many ephemeral streams, and thus do not represent clear water infiltration rates at steady-state.

The procedures discussed above were used to calculate representative runoff and transmission loss values for the watersheds of the Oracle Agricultural Center in an average year. Results are given in Table 8. These values will be used later in design of water harvesting/runoff farming systems for OAC.

Micro Catchments

Establishment of small test plots for obtaining on-site runoff data may be necessary before the final design for micro catchments is completed. Information is needed on peak rates of flow and total seasonal runoff, and designs based solely on theoretical estimates are always risky. One or two years of field observations from small plots has been justified even if this data collection period delayed the project by a year (Shanan and Tadmor, 1979).

Shanan and Tadmor (1979) discussed use of the hydrologic equation to calculate runoff from micro catchments for a specific storm period as expressed by the relationship:

runoff = rainfall - interception storage - depression storage - infiltration.

Rain gauge measurements do not take into account rainfall intercepted by vegetation which remains on the catchment. Interception losses vary with plant density and are small in arid areas. Interception loss can usually be neglected, but in regions where average rainfall is 250 mm and plant cover 40 - 60 percent, interception losses will reach 0.8 - 1.2 mm per storm and may be a significant factor in reducing the runoff from micro catchments.

Depression storage (rainfall trapped in shallow local depressions) is a function of two factors--surface slope and surface irregularity. The following values are recommended by Shanan and Tadmor (1979) for estimating depression storage:

a) on areas where overland flow length is less than 0 m, and slope greater than 3 percent, depression storage will probably be less than 0.3 mm per storm;

b) on areas where local depressions are difficult to discern and where standing water is not observed in puddles immediately after rainfall ceases, depression storage will be from 0.3 to 1.0 mm per storm;

c) on areas where water accumulates in local depressions with a depth of 5 - 10 mm, depression storage will be 2 - 4 mm per storm.

Infiltration capacity for micro catchment design can be determined from:

a) ring infiltrometers, and

b) artificial rain simulators on small plots.

Table 8. Runoff and Transmission Losses for Watersheds of the Oracle Agricultural Center

		Watershed A*		Watershed B**	
Rainfall (mm)	Number of events	Runoff (1000m^3)	Transmission loss (1000m^3)	Runoff (1000m^3)	Transmission loss (1000m^3)
3	15	0	0	0	0
7	7	0	0	0	0
15	7	0.5	0.3	1.2	0.8
32	5	11.1	3.9	25.2	11.7

* 190 ha
** 433 ha

Vegetation generally has a greater influence on infiltration than soil type and texture. Infiltration capacity increases with rising temperatures as the viscosity of the water decreases. The temperature of both water and soil affect the relationship.

The effect of stone cover on infiltration rates is complicated. On non-crusting soils stones act as a protective mulch, reduce the sealing effect of the raindrops, and increase infiltration rates. But on crusty soils, partial stone cover of an area has the reverse effect due to the role played by air entrapped in the soil (Shanan, 1975).

Infiltration rates are also a function of rainfall intensity mainly because raindrops rupture the soil crust and momentarily increase infiltration. Other factors affecting the infiltration capacity of a particular area include (1) initial moisture content of the soil, (2) shrinking and swelling of colloidal material in the soil, (3) macro-openings in the soil due to the decay of roots and the activities of burrowing animals, (4) compaction, (5) depth of the water flowing over the area, and (7) turbidity of the water.

Runoff from untreated micro catchments at the Oracle Agricultural Center was calculated using the procedure suggested by Shanan and Tadmor (1979). The equation used was:

$$R = C(P - T)$$

where

R = runoff

C = coefficient = 0.4 (for cleared watershed)

P = precipitation

T = threshold rainfall = 2.7 mm (for cleared watershed)

Results are shown in Table 9. These values will be used later in designing a micro catchment water harvesting system.

Soil

Soil must be looked at from two viewpoints as regards its suitability for water harvesting/runoff farming systems. First it is the medium for plant growth, and because water supply may be both irregular and infrequent, it should be 1.5 - 2.0 m in depth for good root development and have high water holding capacity with more than 20 percent clay in the "B" horizon (Mielke and Dutt, 1981). At the same time, it must accept water quickly (have a high infiltration capacity). These two criteria are sometimes in conflict. Soil fertility must be given the same consideration it gets in any crop production system. If salinity is a problem, soils must be reclaimed by leaching or amendments (Flug, 1981), and other treatment may be necessary to reduce disease problems.

Table 9. Runoff from Micro Catchments at the Oracle Agricultural Center

Rainfall	Runoff from Microcatchments 1/m width	 3 m width	 5 m width
(mm)	(m^3)*	(m^3)*	(m^3)*
3	.00012	.00036	.0006
7	.0017	.0052	.0086
15	.0049	.015	.025
32	.012	.035	.059

* cleared, 3 percent slope, width along slope as indicated, per meter of length

Soil then must be considered as the surface of the watershed. A tendency to crust is useful in increasing runoff (Flug, 1981). Clay content should be 5 - 25 percent for best compaction; soil with less than 5 percent clay cannot be compacted (Laing, 1981). Mixed clay mineralogy is preferred (kaolinite, illite, and montmorillonite) or soils must be low in montmorillonite and illite to avoid excessive cracking (Dutt, 1981; Laing, 1981). Cation exchange capacity should be less than 6 meq/100 g soil; exchangeable sodium percentage (ESP) should range from 5 to 15 percent (Laing, 1981).

Soil in the cultivated area may be treated for three purposes: to increase infiltration, to reduce evaporation, or to increase water storage capacity in the root zone. Infiltration will be increased by 1) increasing infiltration opportunity time - levelling or diking to hold the water on the surface longer; 2) increasing permeability (hydraulic conductivity) at the soil surface - adding soil amendments, organic material or surface mulching, or 3) increasing hydraulic conductivity in the root zone - vertical mulching, treated holes or sand columns, or placement of plastic tubing from the surface to the deep soil zone.

Evaporation will be reduced by surface mulching using such things as coarse sand, gravel, or pumice or by covering with light weight plastic sheets. Evaporation also is reduced by getting more water into the deep soil zone.

Water storage capacity (available water) in the root zone will be increased by soil amendments - gypsum, manure, or organic material, or by mixing the existing soil with other soil material to obtain more desirable size distribution characteristics. The various soil treatments are listed and rated for effectiveness in Table 10. Soil water storage for typical soils is given in Table 11. Note: Keep in mind the need to prevent excess moisture in the root zone when crops are present and the possible need for leaching to prevent build-up of salts in the soil.

Soil pH may need to be adjusted to reduce the effects of bacteria or fungi. For example, in Southern Arizona addition of sulfur is necessary to limit the possibility of root rot.

Soil factors which will determine crop type, physical characteristics of the water harvesting system, and watershed treatment methods can be listed as follows:

- soil type or classification
- profile (layering)
- depth
- uniformity (within area of water harvesting system and associated watershed)
- clay content
    - percent
    - mineralogy (types of clay)
- infiltration characteristics
    - effect of time
- moisture storage characteristics
    - mm of available water per m (depth) of soil
- acidity/alkalinity (pH)

Table 10. Summary of Treatments to Increase Infiltration and/or Reduce Evaporation on Cultivated Areas in Water Harvesting/Runoff Farming Systems

	Effectiveness in		
Treatment	Increasing Infiltration	Reducing Evaporation	Increasing Soil Water Storage
levelling	moderate	n/a	n/a
diking	high	n/a	n/a
soil amendments	moderate	n/a	moderate
surface mulching	moderate	high	na/
vertical mulching	high	n/a	moderate
treated holes (sand columns)	moderate	slight	moderate
plastic tubing*	moderate	slight	moderate
soil mixing	moderate	n/a	high

*from surface to deep root zone.

n/a - not applicable

Table 11. Soil Water Storage

Soil Type	Available Moisture Range mm/m	 Average mm/m
Very Coarse to Coarse Textured Sand	40 - 100	75
Moderately Coarse Textured Sandy Loams and Fine Sandy Loams	100 - 150	125
Medium Texture - Very Fine Sandy Loams to Silty Clay Loan	125 - 190	160
Fine and Very Fine Texture - Silty Clay to Clay	130 - 210	175
Peats and Mucks	170 - 250	210

* Available water = field capacity - water at permanent wilting point

- erosion hazard
    - low, moderate, high
- salinization or salinity hazard
    - low, moderate, high

Terrain

Characteristics of the terrain will determine the most suitable type of and the best location for the water harvesting/runoff farming system (catchment and cultivated areas, stream diversion point and terraces, or area for water spreading). Gently sloping surfaces without gullies, channels, and depressions are easier to adapt for water harvesting (Flug, 1981). Slopes of about 3 percent have no depression storage (Fink and Ehrler, 1981). Slopes greater than 7 - 8 percent have erosion problems, particularly if the flow path is longer than 10 m (Shanan and Tadmor, 1979; Frazier, 1981). Access to the site is important for construction, operation, and maintenance and may be affected by the terrain.

Relief should not be great for ease in construction and maintenance. Although terraces have been constructed in areas of high relief, they are more difficult to manage and maintain there than in areas of less relief.

The aspect of the land controls the microclimate. For example, does the area get full daylight sun? This will be important during the cooler parts of the growing season, if there is a cool season.

The amount of gullying (erosion) which has taken place may limit the usable area and also will indicate the extent to which erosion may be a problem for a new installation. The drainage pattern determines the space available for and shape of the system to be installed.

Vegetation (Crops) and Water Requirements

The indigenous and exotic grasses, shrubs and trees found in the area being considered will help determine runoff and the most suitable crops for water harvesting in that location. Knowledge of locally cultivated crops (irrigated or rainfed) and other desired crops will integrate local concerns into planning. What do people want to grow? Their interests must be considered, particularly in introducing new crops. Crops known to have been successfully grown with water harvesting systems are listed in Table 12.

Crop water requirements (moisture deficits) and stress conditions must be known or calculated for all crops being considered to determine their suitability and the physical relationship of catchment and cultivated areas for micro catchments. Each crop has a definite water requirement for each stage of its growth cycle. The requirement is modified by the environment in which it is grown. Temperature and relative humidity are major modifiers. Data on water requirements for various crops have been determined and tabulated (Doorenbos and Pruitt, 1977; Erie, et al., 1968). If more accurate data are not available, a seasonal estimate of total use can be used. Weekly data are preferred. An example of the type of information needed is given in Figure 12.

Table 12. Plants Successfully Grown in Water Harvesting/Runoff Farming Systems

Plant	Yield (Kg/Ha)	Increase in yield/ growth (%)	Seasonal Rainfall Zone (mm)
Grains			
corn	1968-6100	6-25	138-425
barley	2290	116	366
wheat			
sorghum	800-2500		140
	2942-4698	0-150	152-183
oats			
millet			
Vegetables			
cabbage	4470		275
squash	27000		275
pumpkin	36900		275
peppers			
asparagus			
potatoes	2700		275
radishes	55700-76700	70-135	330
beans	5000		275
cucumber	14100		300
beets	11700-16100		275
tomatoes	5400		275
onions	7800		275
turnips	9100		275
carrots	15800-25700		275
Fruit trees			
olive			
peach			
apricot			
fig			
pomegranate			
apple			
nectarine			
pear			
plum			
Nut trees			
almond	583-808 gm/tree		225
chestnuts			
pistachio			
Other trees			
quetta (Afghan) Pine			
Arizona cyprus			
Scotch pine (*Pinus sylvestris*)		31	483
Red cedar (*Juniperus virginiana*)		32	483

Table 12. Plants Successfully Grown in Water Harvesting/Runoff Farming Systems (con't)

Plant	Yield (Kg/Ha)	Increase in yield (%)	Seasonal Rainfall Zone (mm)
Vines/trees			
grapes			370
raspberries			
cantaloupe	8500		300
watermelon	7300-23700		275-300
Forage			
blue panicgrass (*Pavicuna antidotal Retz*)	2500	400	125
buffel grass (*Cenchuo ciliaris*)	649-940	1850	240
Lehman lovegrass (*Eragrostic lehmanniana*)	365-436	700-900	240
Miscellaneous			
sunflower			
jojoba			
fourwing saltbush (*Atriplex canescens*)	87-184	144-312	317

Sources: Dutt, et al., 1981
Frasier, ed, 1975
School of Renewable Natural Resources, 1982

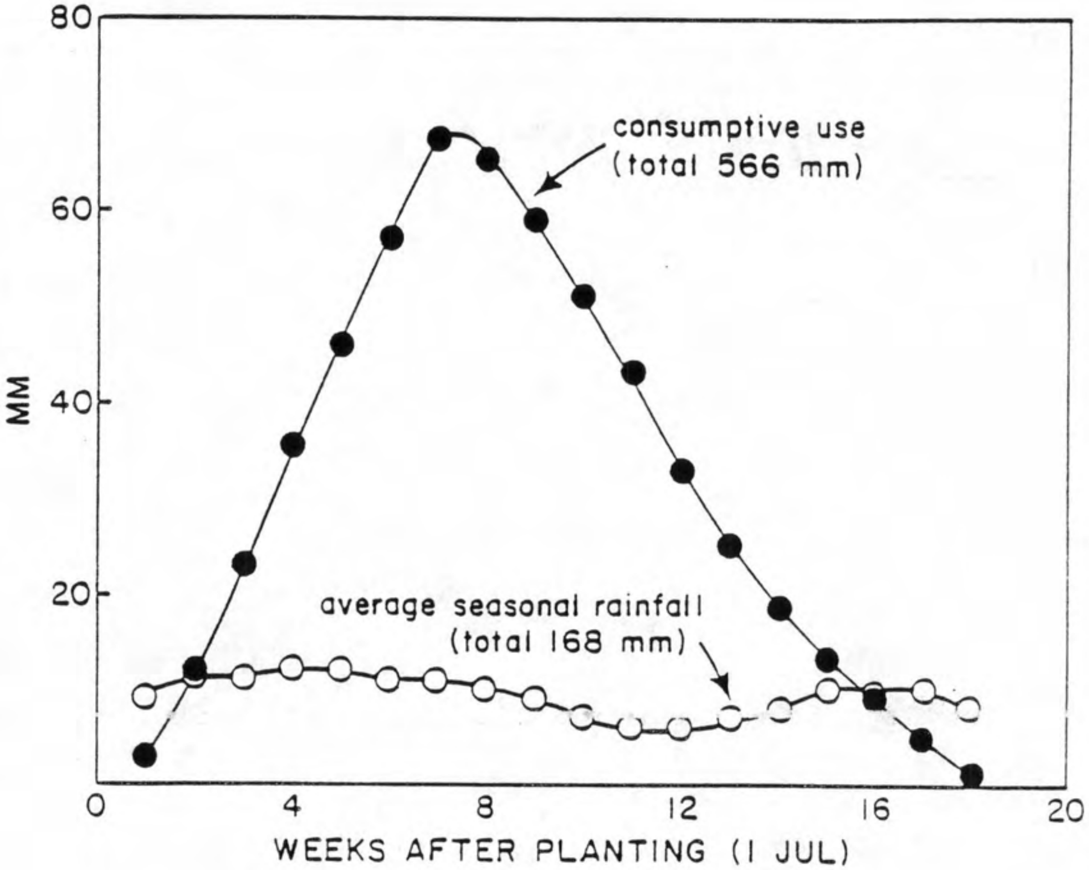


Figure 12. Rainfall and Crop (Sorghum) Water Requirements at OAC.

Crop production functions of water which show the yield obtained with various amounts of available water must be known to determine potential yield for economic evaluation (Figure 13). An approximate production function can be developed when none is available for the specific location by using data from several nearby locations of greater or lesser rainfall (Figure 14). Indigenous plants (not always thought of as crops) can be made substantially more productive with a little extra water.

Crops selected should be adapted to the soil and climate of the region and if possible should match the precipitation and runoff pattern (Flug, 1981). They should have a low water requirement, be drought tolerant, have deep rooting systems, and have high value in the marketplace (Mielke and Dutt, 1981).

Planting date may be arbitrary for some annual crops in areas of long growing seasons. For example, researchers in Brazil have determined that for water harvesting systems there, planting just before the rainy season is advantageous to avoid the high evapotranspiration losses of earlier or later planting dates (Porto, 1982).

Storage Potential and Loss Reduction

Storage of excess water in small reservoirs is frequently a part of water harvesting/runoff farming systems. Reservoirs may be made by damming up the stream channel, by excavating surface materials, or by constructing banks (dikes) on the surface. A reservoir may be located above or below the cultivated area. Most commonly it is below, to catch excess runoff which can't be absorbed immediately in the cultivated area.

The actual need for storage is a function of the difference between available water in the root zone (rainfall + infiltration from runoff applied to the cultivated area - losses) and crop needs, which obviously also depends on the type of system used and its characteristics. Unless rainfall is uniformly distributed throughout the year, production of perennial crops likely will require provision for storage of excess water and subsequent application during long dry periods. Annual crops often can be grown without storage. For storage need determination, a water budget for the proposed crop and system characteristics must be made on a daily basis if adequate data are available, or on a weekly, monthly, or seasonal basis, in that order of preference.

The decision of whether or not to include reservoir storage as part of a water harvesting/runoff farming system is based on several interrelated factors:

1. normal rainfall variability to be expected in the growing season,
2. duration of normal periods without rain during the growing season, particularly for perennial crops,
3. availability of excess rainfall and/or runoff at a time when it can be stored economically for later crop use,
4. appropriate site for a reservoir,

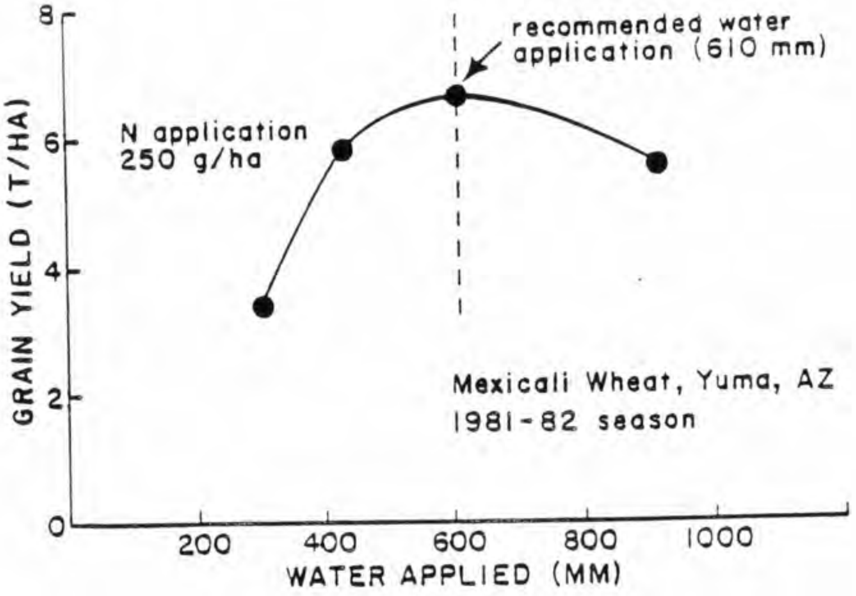


Figure 13. A Crop Production Function of Water
Source: Roth, 1983.

*Foliage growth (which might be forage) can be significant even when grain yield is zero.

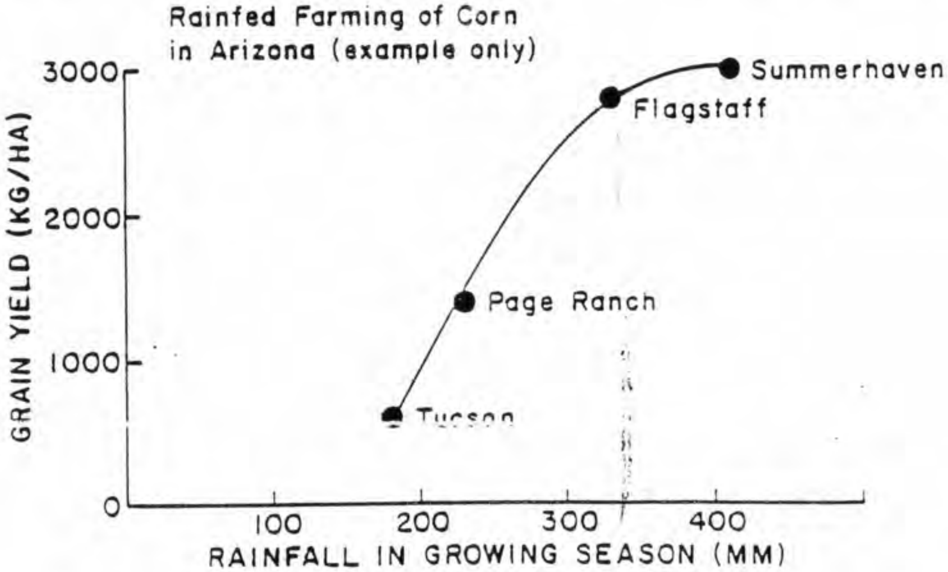


Figure 14. Use of Data from Locations of Different Rainfall to Approximate a Production Function

This example uses data from several Arizona locations to determine possible yield of corn (grain) with different amounts of water available.

5. soil moisture storage capability, and

6. capability of the users (farmers) to withstand the economic hardship of crop failure or greatly reduced yield when it occurs.

Losses from reservoirs are by evaporation and seepage. Evaporation can be reduced by reducing the solar energy that penetrates the water surface, by reducing the water surface area or by placing an impermeable or slightly permeable barrier at the water surface. Some methods actually have a combined effect.

Barriers include such things as long-chain alcohols (e.g., hexadecanol) on the water surface; floating covers and various plastic, wood, sheet metal, concrete, or other low-cost covers. Floating covers form an energy and/or vapor barrier. Work with foam-filled glass bottles and plastic film cans as floating covers appears to be promising in Arizona. Foamed, closed-cell rubber sheeting, although more expensive, is used as an anchored floating cover or a freely floating cover in vertical walled steel tanks (Dedrick et al., 1973). This method is adapted for larger reservoirs through the use of a frame to form individual rafts that resist flooding by wave action. Floating blocks of wax are used in vertical-sided tanks. Expanded polystyrene rafts are coated with wax to protect them from atmospheric degradation and weed growth, and to add weight for improved stability. The coated squares are coupled together to form a continuous, flexible, floating cover that will move with the water level. A special barrier can be provided by filling a reservoir to the top with uniform gravel or rocks and then covering it with plastic and soil. An opening for water entry must be provided in this method which obviously reduces reservoir capacity by as much as 70 percent.

Reduction in surface area is accomplished by constructing reservoirs as deep as is practical for the volume stored or deepening existing ones, by choosing a circular or square shape (as opposed to a rectangle or irregular shape), by diking shallow areas so no water accumulates there, or by using a compartmented reservoir as described by Cluff (1977, 1981). The compartmented reservoir reduces both surface area and water temperature by division of a reservoir into compartments and systematic transfer of water between compartments. A schematic of the compartmented reservoir system is shown in Figure 15.

The receiving compartment (A) is below the source grade and may be shallow. Compartments B and C are smaller in surface area but of greater depth. As runoff occurs during the rainy season, the reservoirs fill. Water is withdrawn as needed from compartment A until the volume of evaporation and seepage losses from B and C is equal to the remaining water in A. At this time, the remaining water in A is pumped to fill B and C. Further evaporation and seepage losses from A are eliminated. Water is then withdrawn as needed from B until the water remaining in B is equal to the unused capacity in C. At this time, the remaining water from B is pumped into C. This eliminates further evaporation and seepage losses from B. Surface area and wetted area thus are kept at a minimum for the amount of water in storage at any given time. A three-compartment reservoir can be shown to have significantly less loss than a single reservoir of the same total volume and surface area (Cluff, 1981).

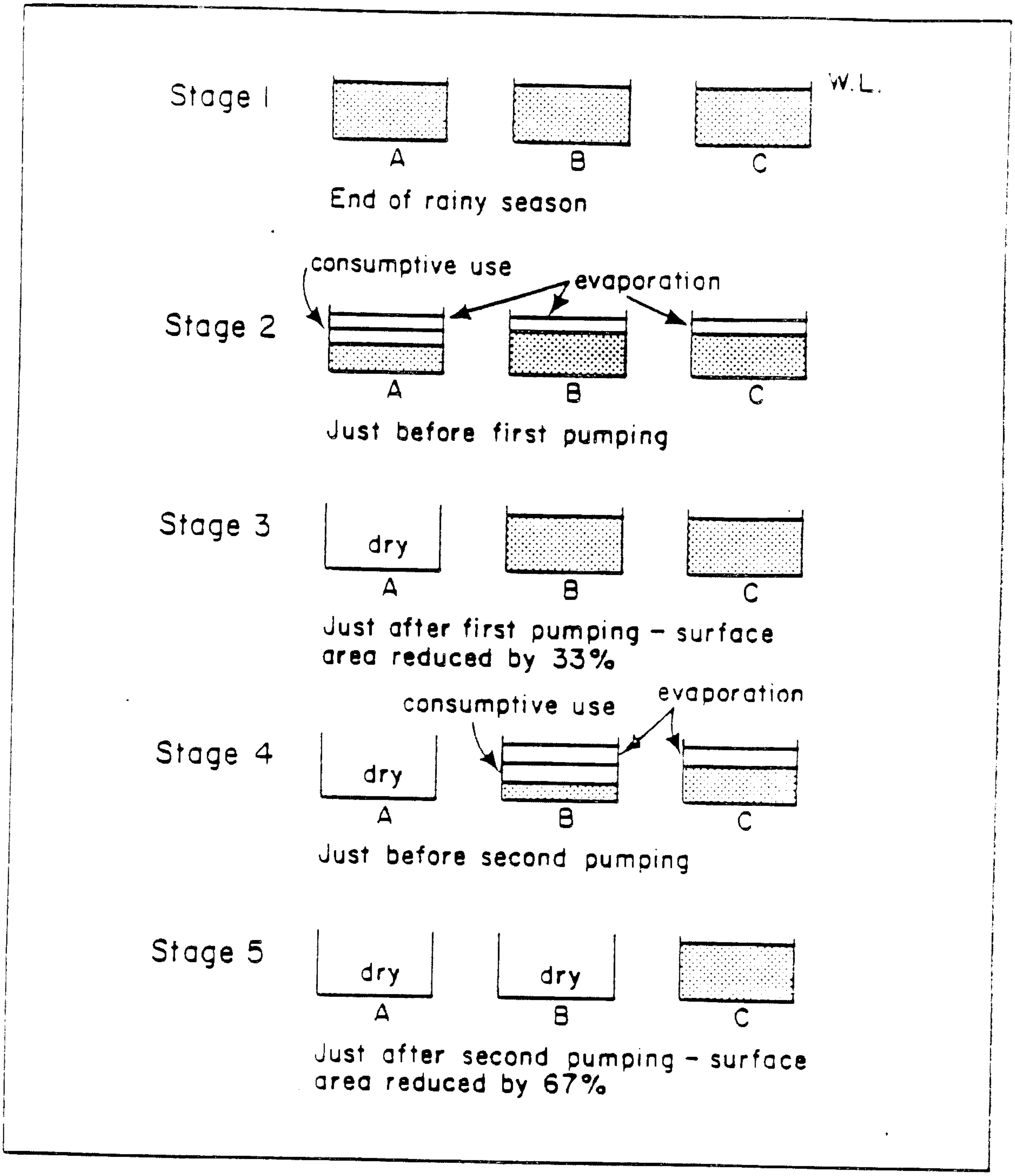


Figure 15. Schematic of three-compartment reservoir showing water levels at various stages in the annual cycle of operation. (from Cluff, 1981).

Since a pump can be used to transfer water, all compartments other than the receiving compartment (A) can be made deeper by building the embankments above the stream grade rather than excavating. This may reduce costs. If the slope of the site is greater than 3 to 4 percent and space for locating the compartments is not limited, a gravity-fed compartmented reservoir can be used with compartments separated by a sufficient distance to develop enough hydraulic head so that one compartment can be completely drained by gravity into the second and succeeding compartments.

Seepage losses from reservoirs can be reduced by several methods (Cluff and Frobel, 1978). Sodium salts such as sodium chloride, sodium carbonate, sodium silicate and sodium polyphosphate act as dispersing agents and reduce infiltration in soils with adequate clay content. The application rate depends on clay content but is about 1.0 to 1.5 kg/m^2. Polymeric sealants such as long-chain silica compounds work best on medium-grained soils where the calcium and magnesium content of the water is high.

Bentonite clay, when wetted, swells to several times its original volume and can be used to form a low permeability zone. It can be mixed with the soil or applied as a layer either buried or on the surface. The mixed or buried layer methods are generally more durable than the surface treatment. A minimum treatment rate of 4.5 kg/m^2 is recommended for soils containing small amounts of sand but application rates can be as much as 15 to 20 kg/m^2 in very sandy soil (Boyer and Cluff, 1972; Rollins and Dylla, 1970). This method should not be used on sites that will be exposed to repeated wet/dry cycles.

Soil cement, a mixture of portland cement, soil and water, can be applied on the reservoir sides and bottom. The amount of cement required increases as the amount of fine material in the soil increases, but generally averages 7 to 15 percent by volume. The soil ideally should be a well-graded material with 100 percent passing a 75 mm screen (Portland Cement Association, 1968). A soil consisting predominantly of gravel-sized particles should not be used for soil cement.

The use of synthetic membranes such as polyethylene, polyvinyl chloride (PVC), butyl and hypalon rubber, and chlorinated polyethylene is more expensive than is the use of sodium salts. However, such liners have long life and compete very well with soil cement and bentonite, particularly if the materials have to be transported very far. Butyl rubber resists atmospheric degradation whereas polyethylene and PVC must be covered with earth. In addition to protecting the membrane from mechanical damage, the earth cover also reduces the seepage significantly through any accidental puncture and is therefore recommended where feasible on all membrane installations.

Poured concrete linings used for seepage control in small reservoir storage projects generally are 5 to 10 cm thick and lightly reinforced with wire mesh. Concrete lining requires skilled labor and special equipment not always found in remote regions. The concrete should be well cured to help obtain watertightness and resistance to weathering.

Plastic sheeting (polyethylene or PVC) can have wire-reinforced mortar applied as a protective cover. This type of lining can be used with mortar-covered sides and an earth-covered bottom which reduces construction cost considerably.

Successful unreinforced asphalt linings for small reservoirs have been catalytically blown asphalt or air-blown asphalt cements of the 50 - 70 penetration range (Hoiberg, 1965). The asphalt membrane must be covered with soil of sufficient depth to prevent atmospheric degradation or mechanical damage. Using fine cover materials, such as sand, on the top of the asphalt and then adding coarse-grained gravel or cobbles provides an erosion-resistant surface suitable for banks.

Exposed asphalt-fiberglass linings can be used for seepage control in small ponds (Myers and Frasier, 1974). The asphalts are either cutbacks (solvent based) or emulsions (water based).

An asphalt-polyethylene-asphalt-chipcoated treatment requires 6 mil thick polyethylene. A protective soil cover of 150 mm or more is recommended (Frobel and Cluff, 1976). Asphalt-concrete mixes of proper design can be used for seepage control.

The costs of these seepage and evaporation control treatments for various reservoir sizes related to water saved are shown in Table 13.

Social and Political Issues

There are many social and political issues which must be addressed before a water harvesting/runoff farming system can be designed, constructed, and put into operation. Knowledge of local agricultural systems, families (as production-consumption units), customs relating to agriculture, population and growth rates will help planners in determining overall suitability for small-scale water management methods and in selecting the type of water harvesting/runoff farming system to be used and its operating characteristics. Short term technical success of new water management systems around the world has lead in many cases to long term deterioration and failure because of inadequate attention to social aspects (Pacey, 1977). Some of the questions to be answered are listed below.

- What are people in agriculture familiar with?
- Is water harvesting/runoff farming known and/or practiced locally?
- What crops are grown now? Are they consumed locally or are some marketed?
- What is the land tenure and use pattern?
- How would land be made available for water harvesting/runoff farming and who decides on the allocations?
- What technical innovations were tried in the past, but failed? Why did they fail?
- To what extent will the proposed system have to be mechanized?
- What is the technological capability of the people? What type of system will be most suitable for their skills and equipment? What training will be required to prepare them for constructing, operating and maintaining the system?
- Will a new work load be imposed? On whom?
- What minimum probability of success is acceptable by local producers? An element of occasional crop failure or reduced yield is part of any water harvesting/runoff farming system.

Table 13. Cost/Unit of Water Saved by Reservoir Treatment

Treatment	$\$/m^3$ Water Saved	Rank by order of cost
SEEPAGE REDUCTION METHODS*		
I Chemical		
Sodium Chloride	.0045	5
Sodium Carbonate	.0057	7
Polymeric Sealants	.012	11
II Wyoming Bentonite		
Pure Blanket (surface)	.029	18
Mixed Blanket	.014	13
III Earth Structures		
Compacted Earth	.0036	3
Soil Cement (10 cm)	.014	13
IV Asphalt		
Asphalt Fiberglass	.0036	3
Asphalt Plastic Asphalt Chipcoated (APAC)	.0064	9
Asphalt Rubber	.0057	7
Buried Asphalt Membrane	.0078	10
Asphalt Concrete (15 cm)	.013	12
V Concrete		
Portland Cement Concrete (15 cm)	.017	15
VI Synthetic Membranes		
Soil Covered Polyethylene Plastic	.0016	1
Soil Covered Polyvinyl Chloride	.0035	2
Reinforced Mortar-Covered Polyethylene Plastic	.0056	6
Chlorinated Polyethylene (CPE)	.019	16
Artificial Rubber	.024	17
EVAPORATION CONTROL METHODS*		
I Structural Methods		
Compartmented Reservoir	.00008	1
II Floating Covers		
Polyethylene 10 mil Sheeting	.00098	2
Wax (paraffin)	.0013	3
Wax-impregnated Polystyrene Foam Slabs	.0015	4
Asphalt Chipcoated Polystyrene Foam Slabs	.0036	6
Foamed Rubber Sheeting	.0017	5
Light Weight Concrete Slabs	.0048	7
III Rigid Roof Structures		
Wood	.015	8
Concrete	.018	9
Aluminum	.019	10

*$450m^3$ reservoir (15m x 15m x 2m), assumed total loss without seepage reduction.

Source: raw data from Cluff and Frobel, 1978
calculations by authors

- What government support is available? Local and national support will be required for research on new technologies and may be necessary to assist in constructing the system.
- What are the pertinent water laws? What are the rights to harvested water and to runoff in ephemeral stream channels?
- Who would be affected either positively or negatively by increased emphasis on water harvesting/runoff farming?
- Who will get the benefits of the new system?
- Who will pay the costs?
- How will water harvesting/runoff farming systems be affected by agricultural policies such as those in price control, subsidies and natural resource conservation?

Health and Environmental Concerns

Implementing a new water harvesting/runoff farming system causes changes in the local environment. Before going ahead with the design and then construction of the system, concerns about the environment must be addressed. The following questions serve as a check-list. Others might be included to represent a particular local situation.

- Will soil erosion be temporarily or permanently increased?

- How will materials used for catchment treatment (to increase runoff) affect water quality on site and in nearby locations?

- How will runoff and ground water recharge be changed as far as other water right holders and water users in the vicinity will be affected?

- Will clearing of vegetation and establishing new crops or trees cause significant changes in habitat for existing fauna or create a habitat for new fauna, particularly pests?

- What long term damage will occur if the project has to be abandoned during or after construction?

Impounding water, even in small reservoirs, may result in increased health hazards. Incidence of malaria, bilharzia (schistosomiasis) or Guinea worm (dracunculis) may increase unless special precautions are taken to avoid them. Water borne bacteria and viruses amy increase.

Ponded water may be a hazard to small children and the aged who could fall into the reservoir. Special precautions must be taken to insure their safety.

Economic Conditions

The final determinant of whether to go ahead with implementing a water harvesting/runoff farming system is the economic rate of return. Will the benefits obtained from the system exceed the costs of construction, operation and maintenance? In some cases certain initial and operating and maintenance costs will be subsidized by the government, but the ultimate success of the system depends on whether the farm families who operate it will know that it has real benefits for them.

When water harvesting replaces traditional rainfed or irrigated farming, the economic analysis must consider that land formerly planted to crops has been taken out of production to form the catchment. Calculation of yield per unit of land therefore should include both cultivated and catchment areas when comparing water harvesting with the system being replaced. The comparison is between high, regular production from part of the land area and low, irregular production from all of the land.

Economic factors which must be known to make such an assessment include the following:

- land values
- land taxes
- cost and availability of other sources of either surface or ground water
- potential net returns per unit of land from existing or other agricultural systems which might be used.
- labor cost and availability for construction and operation and maintenance
- cost and availability of construction equipment and materials
- cost and availability of capital and financial services
- characteristics of local and regional agricultural markets
- potential for marketing crop surpluses and new crop products

A cost-benefit analysis of micro catchment water harvesting in Israel predicted negative income (losses) where precipitation was less than 150 mm. (Oron, et al., 1983) Table 14 summarizes their analysis which shows the added value of inserting plastic tubing near almond trees to get more water into the deep soil zone and thus increase soil moisture storage.

Table 14. Economic Evaluation of Water Harvesting

Contributing Area m²	Income				Expenses			Net Return			
	150mm Rainfall Zone		250mm Rainfall Zone					150mm Rainfall Zone		250mm Rain Zone	
	MCWH	MCWH + Insert	MCWH	MCWH + Insert	MCWH	Insert	Total	MCWH	MCWH + Insert	MCWH	MCW Inse
1000	31.1	48.4*	52.9*	70.3*	60.8	5.8	66.6	-29.7	-18.2*	-7.9*	3.
750	33.7	56.9*	60.5*	83.7*	64.8	7.8	72.6	-31.1	-15.7*	-4.3*	11.
500	36.5	71.2	72.2	106.9*	72.4	11.7	84.1	-35.9	-12.9	-0.2	22.
250	34.9	104.2	92.9	162.4*	91.1	23.4	114.5	-56.2	-10.3	1.8	47.
200	30.9	117.7	98.8	185.6	100.5	30.8	131.3	-69.6	-13.6	-1.7	54.
100		170.7	106.7	280.5	126.2	58.4	184.6	-126.2	-13.9	-19.5	95.
50		244.5	74.5	421.6	163.6	116.8	280.4	-163.6	-35.9	-89.1	141.

All prices are given in U.S. dollars/ha/yr.

A negative sign indicates a loss

MCWH - microcatchment water harvesting

*Although given for water application higher than 6000 l/tree, other factors should be considered in the yield function.

Source: Oron, et al., 1983.

3. SYSTEM DESIGN AND CONSTRUCTION

Information is provided in the following sections as a guide to designing and constructing water harvesting/runoff farming systems. The design process involves a series of compromises as the pertinent factors are considered and given priorities. Specific design methods for water spreading, diversion systems, and micro catchments are presented.

Design of water harvesting/runoff farming systems is not an exact science. For this reason, all applications, even though some are not intended for research, should include a research component so that learning will continue. Variations in site preparation, size relationships, planting date, and cultivar planted should be included. In this way people for whom and by whom these systems are being installed will not be discouraged if some of the original design parameters turn out to be slightly in error. Because few practitioners of water harvesting have all the skills required for good design, it will be useful to consult with experts in hydrology, climatology, plant science, soil science, engineering, economics and other social sciences.

Good design is the fundamental basis for successful water harvesting/runoff farming systems, but equally important are the skills and techniques used in constructing the system from the design. Flood water will always find the weak points in the system and wash out embankments, silt up ditches and generally cause havoc (Shanan and Tadmor, 1979). Repairs are virtually impossible during flood flow, and much time, energy, and valuable water may be lost. Effective water management, even on a small scale, requires close attention to detail.

There are several different methods of construction or materials which might be used for water harvesting/runoff farming systems depending upon the factors previously discussed and the characteristics of the design. In some cases special equipment has been developed for construction of these small scale water management systems. But one of the advantages of water harvesting/runoff farming technology is that by virtue of its small scale and usual location on the upper reaches of watersheds, all of the construction can be carried out by hand labor and hand tools if other methods are not possible. Availability of animal power and/or some simple machinery obviously will speed up the construction process.

Design Summary

The design of water harvesting/runoff farming systems is a complex process. Many of the important design factors cannot be determined precisely. Therefore the designer must be extremely careful to avoid oversimplification and to follow all necessary steps. Recently an attempt has been made to model the design process of reservoir-based systems using computer technology. Cluff (1977), and Shanan and Tadmor (1979) have discussed engineering and soils aspects of micro catchments in some detail. Their approaches are helpful under certain circumstances and to the extent that they cover the overall topic.

The design process for all types of water harvesting/runoff farming systems involves a series of logical steps. The steps which are followed are not always the same, nor are they carried out in the same order. Furthermore, they often are interdependent, and the designer must repeat the process frequently after making some of the choices and calculations. Information about the design factors described in the previous chapter is the basis for decision making. In summary, the general process of design is as follows:

- preliminary determination of technical, economic and social feasibility
- selection of type of system and an appropriate location
- determination of need for and siting and design of external protective structures to prevent uncontrolled flooding
- determination of cultivated area availability, shape and dimensions, surface and subsurface soil treatments, and potential soil water storage
- crop selection and determination of water requirements and water stress characteristics
- siting and design of spreading and diversion dams and associated structures
- siting and design of water conveyance channels and determination of seepage loss reduction treatments for them
- selection of catchment shape, treatment, area ratio, and dimensions and determination of effect on water quality
- determination of reservoir need, seepage and evaporation loss reduction treatments, shape and dimensions
- design of surface flow distribution structures within the project area
- locating and designing protective spillways and other internal erosion control structures
- design of pumpback system and water distribution network, if reservoir is used
- determination of instrumentation required for system monitoring and evaluation
- determination of cost/benefit ratio
- review of design process to reaffirm feasibility of implementing the plan and to improve calculations of design parameters.

Preliminary Steps

When information about all of the design factors of Chapter 2 has been obtained and analyzed, planners and designers can start making decisions on whether to go ahead with the project and on the most favorable location(s) for water harvesting/runoff farming systems. They can select the appropriate type of system to be used. Research needs can be identified. Details of the design and construction processes for the major types of water harvesting/runoff farming systems are given in the following sections.

Feasibility Determination

Determination of feasibility of water harvesting/runoff farming systems involves technical, economic, social and political factors. A preliminary determination must be made before investing a lot of time and money in the system, but detailed data commonly are lacking for adequate evaluation. This dilemma is resolved by a dynamic process with continuous feedback of new information as it becomes available.

Technical feasibility is largely based on availability of natural resources--water and soil. Economic feasibility is a function of costs of constructing, operating and maintaining the system, expected returns (profit) and comparison with alternate production systems (uses of resources). Social and political feasibility can only be determined from surveys and discussions with the people concerned and their local and national governments.

The social survey should be designed to obtain information about the following items: 1) perceived needs of the people, 2) their desire to participate in self-help projects, 3) patterns of land tenure and use, 4) water rights, 5) willingness and capability of people to be involved in operation and maintenance activities, 6) system of allocating benefits to the individuals, and 7) indigenous political and social institutions. The results of the survey then can be incorporated in the design (Cotgageorge and Henderson, 1983).

Site and Type Selection

Selection of the type of water harvesting/runoff farming system to be used is based largely on technical considerations of water and land (soil) availability. Each type has advantages for certain physical situations. For example, water spreading and micro catchment systems require relatively flat land. Terraces often are used in hilly to mountainous terrain. A combination of types may be appropriate in some locations.

Topographic Survey and Map

An accurate, detailed topographic survey map of the selected site is the basis for planning and carrying out construction of a water harvesting/runoff farming system. The topographic survey should be made to a scale of 1:2500 or 1:5000 and should include all peripheral areas that will determine the need for any diversion ditches or dikes to prevent uncontrolled flooding. Where no treatment to increase runoff on the catchment area is planned, there is no need for topographic detail on that part of the system.

For micro catchment planning, a 25 cm contour interval and a 1:1000 scale are recommended for detailed design and require about 30-40 survey points per hectare. In exceptionally flat areas with slopes less than 1 percent, a smaller contour interval (say 15 cm) may be required to show the details of the topography (Shanan and Tadmor, 1979).

The map should show all topographic features (rills, gulleys, saddles, hollows, depressions and ridges). Standard land survey methods and equipment can be used for making the detailed topographic map. Where such equipment is not available, hand levels or similar devices can be used to determine high and low points and differences in elevation.

A general plan of the entire water harvesting/runoff farming system should be drawn on a copy of the topographic map or on transparent material so it can overlay the map. This will be very useful during the remainder of the construction process.

Protective Structures

In some water harvesting/runoff farming projects, protective structures (embankments or dikes and diversion ditches) will be specified to prevent undesirable runoff water from entering the project area and damaging the system. Embankments or diversions to control such runoff are designed on the basis of hydrologic analysis of the surrounding area (Shanan and Tadmor, 1979).

The drainage area for each control structure must be delineated satisfactorily, and the design should be verified by a field inspection. Peak flows should be estimated accurately and compared to flows determined from high-water flood marks found in the field.

The capacity of diversion ditches should be based on estimated peak runoff for a given recurrence interval (usually something from 25 to 100 years) and bottom widths and side slopes designed according to the soil conditions and available construction equipment.

Permissable velocities, dimensions and gradients of ditches, and the velocity of flow should be determined according to accepted hydraulic design standards. "Over-design" of structures is preferable to "under-design." Increasing the capacity of a diversion ditch or an embankment by a factor of 50 percent raises construction costs by about 5-10 percent and the additional protection usually is fully justified by the marginal cost.

The detailed plan should include instructions and specifications for construction. In ditches where gradients are greater than 0.4-0.6 percent velocities become erosive, therefore gradients should be kept below these limits. This may require increasing the length of the protective ditch but the extra cost of the extension is usually less than preventing erosion. The runoff carried by diversion ditches wets the bottom of the ditch, and suitable vegetation can be planted there to stabilize them. Since vegetation reduces the capacity considerably, larger ditches must be designed.

Embankments must be constructed carefully because a single weak point is sufficient to cause failure. The center lines of the proposed structures should be laid out accurately. Cross-sections also should be surveyed for major structures. Where embankments cross gullies, the gullies must be shaped before filling and the surface below the structure cleared of vegetation and stones so that the fill material bonds with the foundation. Earth embankments should be constructed so that the height and shape called for by the design are maintained. The uppermost protective embankments and diversion ditches should be constructed first. Criteria for construction of embankments are described in hydraulic handbooks.

Embankments are constructed by hand, animal-drawn scrapers, or with bulldozer equipment and then compacted. Final heights must meet design requirements. Diversion ditches are built by hand, animal-drawn plows, or with motor graders. The earth excavated from a diversion ditch may be placed to form a parallel protective embankment. When drop or overfall structures are needed at the end of a diversion ditch or where sudden changes in elevation occur, erosion can be prevented by using carefully placed rip-rap on the bottom and sides of the channel.

Land Shaping and Smoothing

The next step is to carry out any general land shaping, smoothing or levelling which may be required. These operations can be done with hand tools and labor, with small equipment and animal traction, or by machines such as tractors and moldboard plows, road graders, land planes, laser equipped levelers and scrapers. Shaping is usually more effective when soil is moist but well below field capacity moisture level.

Water Spreading

Water spreading is the simplest type of runoff farming system wherein the cultivated area lies in and immediately adjacent to an emphemeral stream channel. When actually in the channel, the water spreading areas become in effect low terraces.

Water spreading is also similar in some ways to the flood recession agriculture practiced along rivers or around lakes or wet season ponds in many countries. The major difference is in the limited time that water is available on the cultivated area of water spreading systems.

Design Criteria

Design of water spreading systems requires a series of steps as follows:

- Determination of feasibility
- Siting of spreading dams (sometimes called check dams)
- Design of spreading dams
- Design of spillways
- Crop selection
- Determination of area behind dams

Water spreading depends on having a significant area for crop production in or near the stream channel. The area must have soil of reasonable hydraulic conductivity and fertility. A high water holding capacity is desirable because of the intermittant nature of the water supply. Channel slope in the spreading area should be less than 5 percent although the method has been used in areas of much greater slope. Water spreading has been successfully used for tree and row crops and forage production.

Suitable earth fill or rock material for constructing the spreading dams must be available. Material used for constructing earth fill water spreading dams should have characteristics similar to those of material used in any small dams; that is, relatively high content of non-swelling or cracking clay (minimum of 20 - 30 percent). Rock materials should be angular, if possible, unless wire baskets (gabions) will be used, and as large as practical.

The spreading dams should be low, usually less than 1 meter in height at the center. (See Figure 16 for physical relationships in water spreading systems.) Spacing between dams is thus

spacing = 1/slope (fraction)

or less. The area above the dam will fill with sediment being carried with the runoff water. The rate of filling obviously depends on the upstream erosion rate.

In some water spreading systems, years may pass before sediments completely fill the area above the spreading dam. Different operating procedures will be required. Sometimes a phased construction process is used with alternating cycles of building and filling. During initial years, water will pond behind the dam, and a drain can be installed to eliminate excess moisture on the surface or in the root zone. Because the sediments are deposited in layers, often with fine materials on the top, frequent cultivation practices to insure good soil structure may be required.

A series of half-moon shaped areas for plant growth eventually will result. The area of each will depend on the spacing of the dams and their length across the waterway. A slight slope toward the center will remain because of the way in which sediment deposition will occur. Cultural practices should be such as to maintain this slope.

The length of spreading dams will depend upon the original lateral slope toward the stream from the area adjacent to the stream. The profile of the dam (Figure 16) shows that the spillway elevation is slightly below the top of the dam (about 10 cm). Dam length is then limited by the contact of the dam with the natural surface of the adjacent area. The flatter the slope of the natural surface perpendicular to the stream channel, the greater the length of the dam, and hence the greater the width of the cultivated area.

The top width of earth fill spreading dams should be such that the top will not be easily eroded. One to two meters is adequate in those cases where dams are compacted by machines. Where hand or animal labor is used, widths of two meters or greater should be used unless special precautions such as protective ground cover or rip-rap placement are used to avoid erosion. The bottom width of the dam should be such as to have a minimum 1 to 1 slope on the faces of the dam. The height of rock dams should be no more than 1.5 times the base width unless gabions are used.

The spillway area must be wide and flat (level) and treated in some way to minimize erosion because it will have flow crossing it in all but the driest of years. Consideration in design must be given to the maximum flow it will be expected to carry, e.g., a 100 year flood. The downstream face of the spillway and area below should be lined with hand placed angular rock. The top surface can be rock lined, soil cement treated, compacted clay, or seeded with a drought tolerant grass or other suitable ground cover.

In selecting crops for water spreading systems, one should recognize that both soil depth (fill) and water availability will be greatest at or near the center of the spreading dam. Perennial crops may be more suitable at that location with annual, shallow rooted crops on the fringes of the cultivated area.

Construction of Water Spreading Systems

After the site is selected and the topographic survey is completed, the next step is to lay out the design plan on the ground. Corners or boundaries

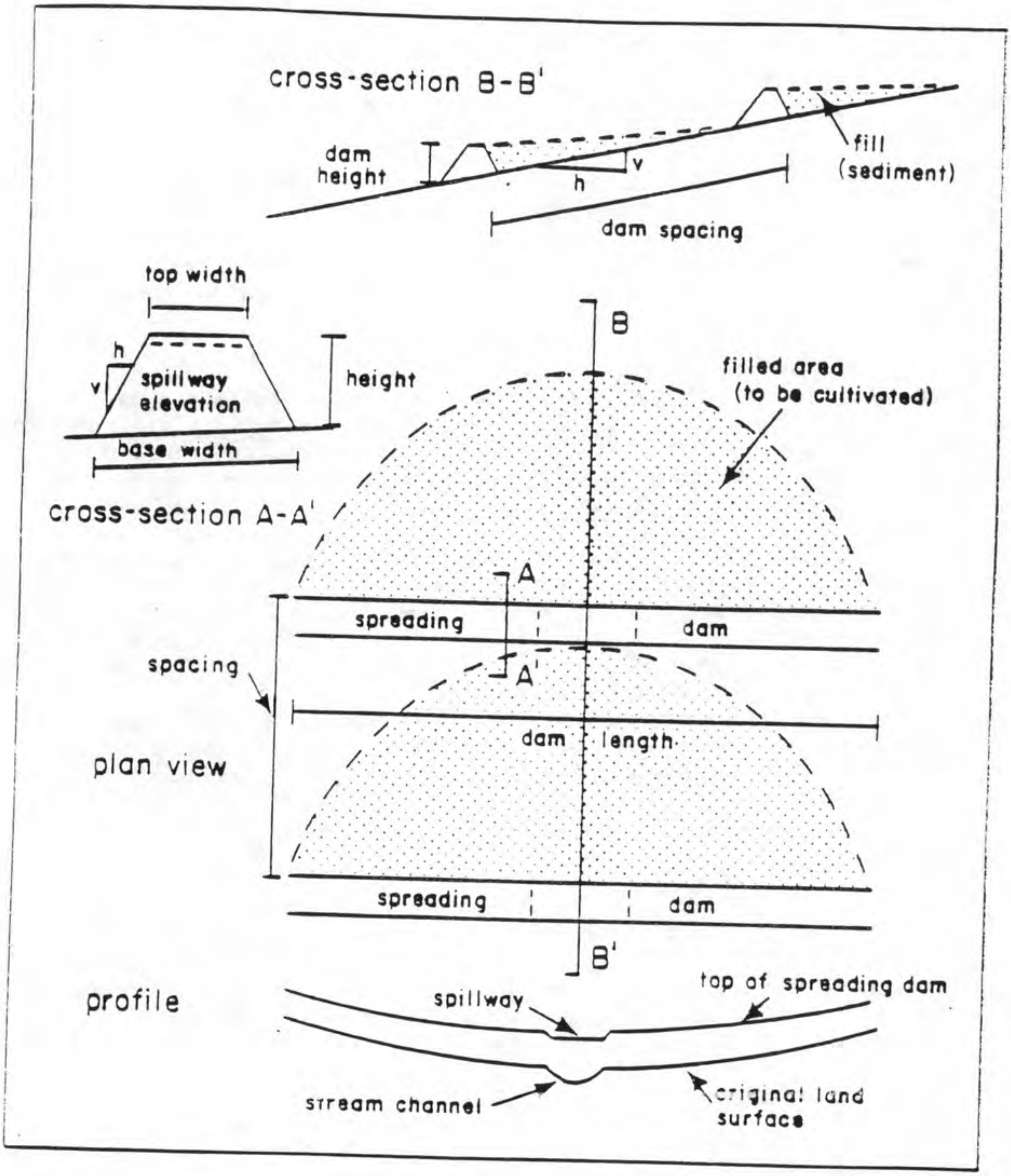


Figure 16. Some Physical Relationships in Water Spreading Systems

and key features should be clearly marked with stakes or other semi-permanent markers.

Spreading Dams. Water spreading dams are usually compacted earth fill or made of carefully placed rock. They can be constructed by hand labor and hand tools or using simple machinery or a bulldozer and accessories.

The centerline of the first dam should be staked across the stream channel to guide the fill process. Stakes must be long enough to reach the upper surface of the dam, or they must be moved upward as the filling operation proceeds.

Clay material should be compacted as it is placed. When done by hand, clay should be moist but not sticky and should be placed in thin layers. Compaction can be done with wooden tampers similar to those used in road construction in some countries. Water-filled rollers like those used for smoothing grass lawns can be used. If large machinery is available, the common sheep's foot roller can be used.

Rock dams are constructed by placing large rocks first and then carefully fitting smaller rocks into the spaces between them so that a massive structure results, not just a pile of rocks. During the first few years while the area behind the dam is filling with sediment, leakage through the dam will be high, and rock movement could occur. This would seriously weaken the dam. Smaller rocks should be placed on the upstream side.

Spillways. The spillway area is critical as it will carry flow in all but the driest of years and hence is subject to major erosion forces. A placed rock (rip-rap) or soil cement lining can be used on the entry, top and downstream sections of spillways on earth fill dams. An apron at the downstream toe of the spillway is important to avoid erosion at that point.

For rock dams the spillway section is equally important and care must be exercised in the placement of rocks in that section so that flow is unobstructed and so that the flowing water will not result in rocks shifting their positions.

Water Spreading Example

A water spreading system is being installed at the Oracle Agricultural Center (Page Ranch). The system will be used for training and research.

Description of area. A watershed of 1.9 km^2 contributes runoff to a 0.5 ha water spreading area at Page Ranch. The area was unused with a vegetative complex of mesquite and Johnson grass.

Design criteria. The feasibility was unquestioned because of the known soil characteristics and availability of space at the site. Slope of the channel was 2 percent. Soil clay content is about 20 percent and is suitable for an earth fill dam. Lateral slope toward the channel was 3-5 percent.

An earth-fill dam 1 meter high with 1 meter top width and 2 meter base was chosen for a site just upstream from a major area of head-cutting erosion in the channel. A topographic sketch of the area and dam was made. A dam of 60 m length was required.

A spillway 10 m wide, 10 cm below the top of the dam was included. The spillway was to be rock lined with a thin mortar layer for stability. The spillway apron at the toe of the dam was to be 2 m in length.

Construction details. The area was staked out and the center line of the dam was marked. A bulldozer was used to push up material from both sides (upstream and downstream) of the dam which was compacted with the bulldozer.

The spillway section is marked out and will be cut in the top surface of the dam. Coarse, angular rock will be hand placed and tamped into the fill material. A mortar layer of about 2 cm thickness will be poured over the rock surface and hand troweled.

Tree crops will be planted in the area near the dam and the channel. Other areas will be used for annual crops.

Other spreading dams and production systems will be added in the future. Different construction methods will be demonstrated.

Diversion and Terraces

This method of runoff farming involves diversion of water from the intermittant flows in an ephemeral channel, conveyance of the diverted water to a nearby location suitable for crop production, and application of the water to a terrace or terrace system constructed for that purpose.

Steps in the design process include determination of the following:

- Possibility of diversion and terrace system
- Area available for crops
- Crops to be grown
- Water required by crops
- Need for reservoir storage
- Location of diversion point
- Type of diversion structure
- Conveyance channel size and shape
- Conveyance losses and possible reduction treatment
- Terrace size (width, length) and layout
- Flow distribution system and operating mode
- Excess runoff and spillways

Feasibility, Area, Crops, and Water Required

The first question which must be asked is, "Are there areas suitable for crop production near an ephemeral channel with unappropriated runoff?" If the answer is yes, then we need to know the total area available for crops. A decision must be made on what crops to grow, and calculations of crop water requirements for each week of the growing season must be made using procedures described earlier.

Water Available

We next need to determine how much water will be available and whether we can plant the entire area which is available for crops. To do this, we examine the climatological/hydrologic data, determine the average number of runoff events likely to occur during the growing season, and calculate the runoff from each, using the procedure described in Chapter 2 or other suitable rainfall-runoff model/equation. We need to know the probability with which we can expect these events to occur. In designing our system, we need to keep in mind that occasional crop failure is inevitable, and we must select design values for runoff amounts which keep frequency of failure at an acceptable level. We need to determine the fraction of total flow which we can divert for the various flow quantities calculated above. This is based on the geometry of the channel at the diversion point.

Need for Reservoir Storage

The need for storage and reservoir size are determined by analysis of water required and water available data. The reservoir should be located close to the terraces so that pumping costs are kept low.

Location and Type of Diversion

The actual diversion point should be selected for ease of access to the channel and where neither sedimentation nor erosion are likely to occur. A straight section of channel is preferred. The diversion structure may be simply an opening through the channel bank (wall) or may include a diversion dam. The diversion dam, which may be temporary or permanent, serves two purposes. First, it raises the level of water so that water flows readily through the opening in the channel wall, and it also serves to direct the flow to the diversion opening if the channel is very wide. Dams may cross the entire channel or extend only part way out into it. In the latter case they intercept a portion of flow which is then directed into the diversion canal. (Figure 17)

Temporary diversion dams may be made of sand, sticks and woven brush or pieces of wood or sheet metal. They will be destroyed by large flows. Permanent diversion dams are made of compacted clay covered with rocks (earth-fill), rocks and mortar, or concrete. The height of a permanent diversion dam should be such that it will be overtopped but not destroyed by large flows.

Water Conveyance and Losses

The conveyance channel connects the diversion to the farmed area. It must be large enough to carry the maximum expected flow. A spillway is provided at the entry point to avoid canal damage from excessive flows. The channel may be merely excavated earth or it may be lined with compacted clay, rocks and mortar, concrete or other materials to reduce seepage losses, particularly important where the application site (terrace) is far from the diversion point. Earth canals should have a slope of about 0.5 percent and a cross section with a wide bottom to reduce velocities and thus lessen erosion. Velocity in earth canals should be less than 0.5m/sec.

A commonly used formula for designing canals is the Manning equation:

$$Q = (1/n) \ AR^{2/3} \ S^{1/2}$$

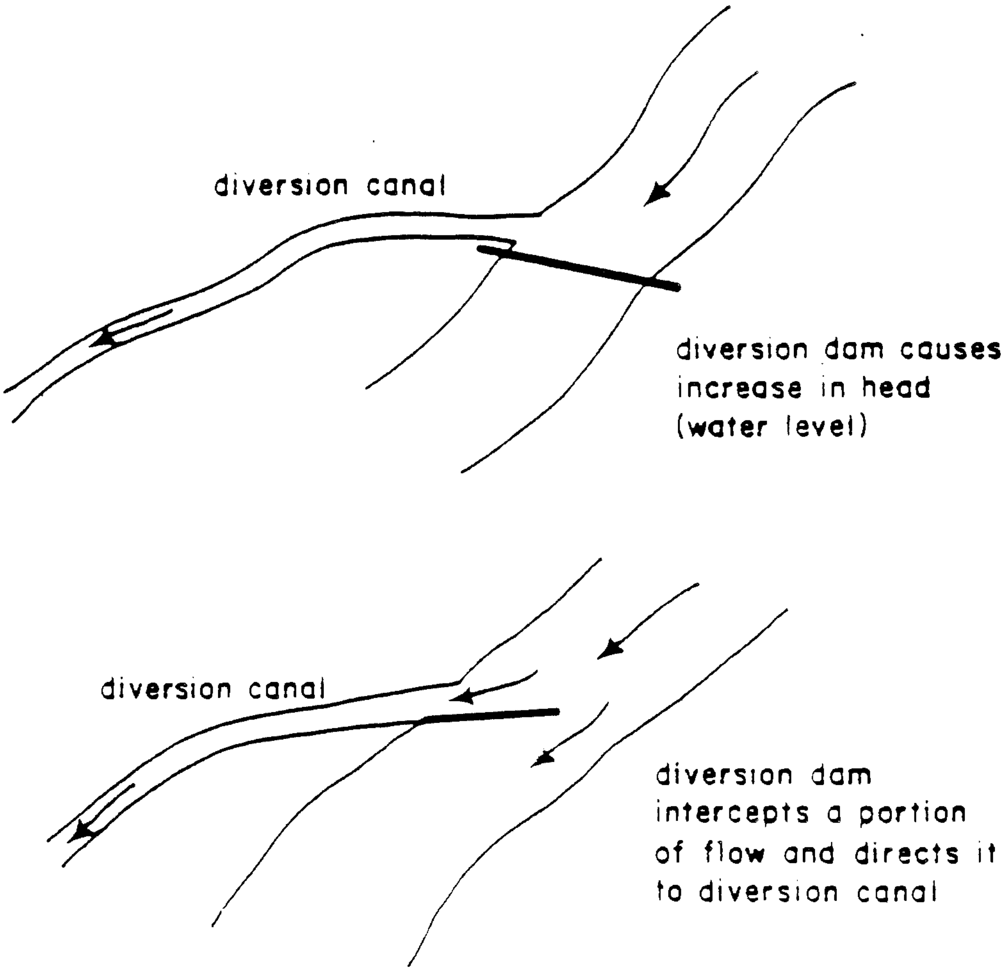


Figure 17. Diversion Structures

where

Q = flow, m^3/sec

n = a friction factor (see values below)

A = area of cross section of flow, m^2

R = hydraulic radius (area/wetted perimeter)

S = slope, m/m

A trial-and-error solution is required. Typical "n" values are as follows:

n	canal material
0.25	earth
0.18	rocks and mortar
0.13	concrete

Conveyance losses must be estimated to know how much water will be available at the terrace site. Conveyance losses for unlined canals may be estimated as follows:

$$S = (0.14/Q)K$$

where

S = loss as percent of canal discharge per km of canal length

Q = canal discharge, m^3/sec

K = saturated permeability, cm/hr

Obviously conveyance loss can lower significantly the quantity of water available.

Terrace Size and Layout

The total area which can be farmed in an average year is determined by dividing the available water by the crop requirements. A larger area should be laid out to take advantage of the excess flow in years of greater than average rainfall. Layout of the terraces will depend on the operating mode chosen; at least three are possible.

Lengths and widths of individual terraces will be determined based on land slope, soil depth and flow quantities and rates to be expected. Terraces in general will be wider on flat slopes, narrower on steep slopes. They will be longer for high rates of flow and shorter for low flow rates. Dimensions will be affected also by which of the three operating modes described below is selected. When terraces are constructed on steep slopes, subsurface drainage may be required to relieve the pressure of excess subsurface water on the retaining dike and must be considered in the design.

Flow Distribution

A first operating mode which can be considered is to deliver all flow onto the top terrace. At the end of the top terrace an overflow structure (spillway) is provided to pass excess flow to the second terrace. The second terrace has a similar spillway to pass flow on to the third terrace, and so on. In this mode the top few terraces likely will always receive enough water; the middle terraces in the system may receive enough; and the last (bottom) terraces will often receive less than adequate water. Crop selection can be made on this basis, for example, perennial tree crops may be placed on the top terraces, less valuable trees or shrubs on the middle terraces, and annual crops or forage on the lower terraces.

The second mode is to place a proportional divider at the head end of the terraces. Assume 4 terraces in a system. At the head of the first terrace a proportional divider passes one-fourth of the flow to that terrace and three-fourths of the flow to the lower terraces. At the head of the second terrace a proportional divider passes one-third of the remaining flow to that terrace and two-thirds of the flow to the lower terraces. At the head of the third terrace a proportional divider passes one-half of the remaining flow to that terrace and the other half to the fourth and last terrace. In this operating mode the head end of all terraces likely will receive adequate water; the middle section may receive adequate water; and the tail end of all terraces likely will not receive optimum water. Again the planting arrangement for the terraces can be chosen in recognition of these differences.

The third mode is to use a system of gates at the head end of the terraces. The gates may be automatically or manually operated. At the initiation of flow the gate to the top terrace is open; a conveyance channel gate below the top terrace prevents flow to the lower terraces. When the top terrace is judged by the irrigator or sensed automatically to have received adequate water, the conveyance channel gate is opened, and the top terrace gate is closed. The second terrace gate is opened and a conveyance channel gate below the second terrace is closed to prevent flow to the terraces below it. When the second terrace has received adequate water, its gate is closed and the channel gate is opened to the third terrace, and so on. This mode permits the greatest control over the amount of water applied to each terrace. For example, the flow sequence could start with the bottom terrace if that was determined to be desirable. It also requires the highest level of management and the presence of an operator (irrigator) during flow events or a sophisticated automatic gate control system.

Excess Runoff and Spillways

The diversion/terrace system must be designed to cope with excess runoff. Excess flow in the conveyance channel is spilled back into the stream channel near the entrance. Additional spillways may be required along the channel if side channel inflow is significant. Drop structures may be necessary along the channel to avoid erosion. Excess flow in the terraces is spilled from top to bottom. But spillways must be provided to prevent washout (erosion) and destruction of the entire system. Excess flow at the bottom terrace can be

77

wasted, stored in a small reservoir for subsequent use or returned to the main or a tributary channel.

Construction of Terraces/Diversion Systems

Diversion Structures. The location of the diversion dam to be constructed across the stream channel is staked out. The location of other diversion structures is similarly marked. Temporary diversion dams are constructed in the stream channel before the rainy (runoff) season. They may last through the whole season or may have to be repaired or replaced during the season. Temporary dams are constructed of brush, logs, rubble, trash, sheet metal, sand, or rocks using hand labor and tools. Permanent diversion dams are made of compacted earth with or without rip-rap or soil cement lining at overflow or stress points, rock masonry or concrete. Excavation of loose materials in the channel bed is necessary before constructing a permanent diversion dam.

Water Conveyance Channels. Canals must be layed out precisely and constructed carefully to maintain the proper grade. Channels for water distribution and control can be hand dug, and linings of compacted soil or clay can be placed by hand. Suitable vegetation can be planted in unlined canals or ditches for erosion control but only if they have been designed larger to carry the same overall flow. The spillway near the canal entrance is constructed of packed clay, soil cement, rock or concrete.

Water Control Structures. Diversion and division structures and drop structures for terraces also can be hand made, but maintenance requirements will be increased. The structure is laid out according to plan. Concrete structures, sometimes hand-plastered in place, will provide long, trouble-free service. Carefully placed rock, with or without mortar, can be used. Construction details of these water control structures are given in publications of the U.S. Department of Agriculture, Soil Conservation Service (1972).

Cultivated Area Preparation. Terrace construction also is detailed in publications of the Soil Conservation Service. The area is first staked out according to plan. Terraces are constructed nearly level using hand tools or machinery with a downstream dike adequate to contain the maximum expected flow. The dikes may be constructed of rock where slopes are great but otherwise are commonly of compacted soil. Where terraces are intended to "spill" excess water to a downstream terrace, a spillway is constructed, usually at the center. The spillway section is lined with rip-rap (hand placed rock), soil cement, or concrete.

Land in the cultivated area of a diversion/terrace system is prepared for planting in the same way that other land in the region or country is prepared for farming. Top soil which is removed in shaping or leveling operations is saved to spread back on the surface afterwards. Subsurface drainage systems can be constructed of clay tile or perforated plastic pipe.

Soil modification to decrease evaporation, increase infiltration or increase storage may be called for by the design. This is accomplished during the construction process by adding material as a mulch, mixing in an amendment, or removing the soil and mixing it as necessary to obtain the desired infiltration and storage characteristics and then replacing it.

Reservoirs and Pumping Systems. Construction details for small reservoirs and pumping systems used to store excess runoff and deliver it back to the terraces are given in the section entitled, Other Facilities, later in this chapter.

Diversion/Terrace Example

A diversion/terrace runoff farming-system is being installed at the Oracle Agricultural Center (Page Ranch). The system is intended for training and research.

Description of area. A watershed of about 4.33 km^2 contributes runoff to an ephemeral stream which crosses Page Ranch. The stream channel is about 7 m wide with a coarse sandy bottom. A nearby unused area is available and has soils suitable for crop production.

Design criteria. The design criteria used were as follows:

Feasibility - water was available near a cultivable area
Area for crops - about 5 ha
Crops to be grown - mix of annual and perennial crops
Water requirements - 50 x 1000 m^3
Water available - 50 x 1000 m^3 (rainfall + runoff)
Need for reservoir storage - none for annual crops, nearby reservoir can be used for emergency irrigation of perennial crops
Location of diversion point - 100 m west of stream entrance to Page Ranch
Type of diversion structure - temporary, mesquite log posts
Conveyance channel size and shape - slope .005, nominal trapezoid
Conveyance losses and reduction treatment - none
Terrace size and layout - 10 m wide x 100 m long, 10 terraces
Flow distribution system and operating mode - proportional dividers
Excess runoff and spillways - excess flow to nearby reservoir

Construction details. A temporary diversion dam 5 m long was constructed of mesquite posts inserted to a depth of 1 m in the sand bed. Brush was interwoven among the posts. This type of structure will wash out in large flows and will be repaired and replaced as necessary.

A canal 0.3 km long was excavated with a tractor and moldboard plow to convey water to the cultivated area.

Micro Catchments

The steps to be followed in design of micro catchment systems of water harvesting are as follows:

- select crop(s).
- select cultivated area shape and dimensions.
- select cultivated area treatment, if any.
- calculate water storage potential in root zone.
- determine water required from catchment and reservoir, if used, on weekly basis (required = available - needed; available = rainfall + storage in root zone and reservoir, if used).

- calculate reservoir storage need + losses (storage need is function of maximum stress period permitted; losses are due to evaporation and seepage).
- review crop selection(s) (is [are] it [they] appropriate?).
- select catchment area type (basins, strips), slope, and treatment, if any
- determine effect of treatment on water quality
- calculate catchment area to cultivated area ratio
- review storage requirements (consider economics of more catchment vs. more storage)
- determine catchment area dimensions (shape and size)
- select reservoir loss reduction treatments
- determine reservoir dimensions
- make provisions for excess runoff throughout the system
- review entire design process, iterate as necessary to improve parameters

Crop Selection

Almost all crops can be grown using the micro catchment system. Selection depends on ecological considerations, i.e., what crops are suitable in the area; what crops are already grown locally, i.e., what crops farmers are familiar with; what crops people want to grow; and what crops are marketable.

Crops may be annual or perennial. The one(s) selected will determine characteristics of the water harvesting system and water requirements. The choice is somewhat arbitrary, but nonetheless important.

Cultivated Area Shape and Dimensions

Annual crops and certain perennial crops, e.g., grapes, are suitable for linear (strip) catchment systems. Most perennial crops lend themselves to individual basin configuration, although the linear arrangement can be used.

The amount of space required per plant is a function of the size of the mature plant and its root system. Estimates of size can be made from observations of existing plants.

In a few cases, the space required by the cultural practices employed can be modified. For example, the meadow system of fruit crop production reduces space needed for each plant (Erez, 1977).

For linear (strip) systems, the width may be one or several plant rows, or several machine widths when mechanized production is used, and the length may be whatever is appropriate for the space available. Micro catchment basins are ordinarily diamond or half-moon shaped with the plant at or near the lowest point. They may be circular with the plant in the center.

Cultivated Area Treatment

The cultivated area may be treated to increase infiltration, to reduce evaporation, or to increase water storage capacity in the root zone as described in Chapter 2.

Water Storage in Root Zone

The amount of water which can be stored in the root zone is calculated on the basis of soil type and treatment applied, if any.

Water Required

Crop water requirements are determined in the same way as described in Chapter 2. To determine water required from the catchment systems (and from storage, if any), the expected seasonal rainfall is subtracted from the total crop need.

Reservoir Storage

The determination of whether storage is required or feasible will be made on the basis of the amount and regularity of expected rainfall/runoff events. The capability of the plant to withstand water stress is the limiting factor. The question of whether excess water is available for storage and when it is available during or close to the crop season also must be answered.

Initially an estimate of storage requirement should be made; the estimate will be improved later in the design process. Losses from the reservoir will occur from evaporation and seepage, and their effect must be included in determining the amount of water required to be put in storage. The reservoir surface, walls, and bottom may be treated to reduce the losses. Effects of treatment will be brought in later in the design process when the storage estimate is refined.

Review Crop Selection

Now that some information has been developed in the design process, consideration should be given to the appropriateness of the crop selected. If crop water needs don't seem to "fit well" with the data assembled, perhaps a different crop should be chosen. If all seems to be in order, the design process can continue.

Catchment Area

The type of catchment area, that is, whether basins or linear (strip) forms are used is determined in part by the crop selection. Other factors of local importance may be considered in the final selection of type.

Catchment area slopes should be between 1 and 7 percent. If slope is too low, depression storage will be significant in reducing runoff. Where slope is too high, erosion problems will be increased. Less than three percent is best for bare catchments; vegetated surfaces can have a steeper slope. Where natural slopes are less or greater, the area can be shaped as shown in Figure 18 to a more favorable slope.

In some cases the catchment area is treated merely to control the runoff by using one or more diversion banks to direct runoff to a waterway or dam.

Many catchment treatments are possible to increase runoff. They have differing effectiveness in producing runoff, different costs, and different

81

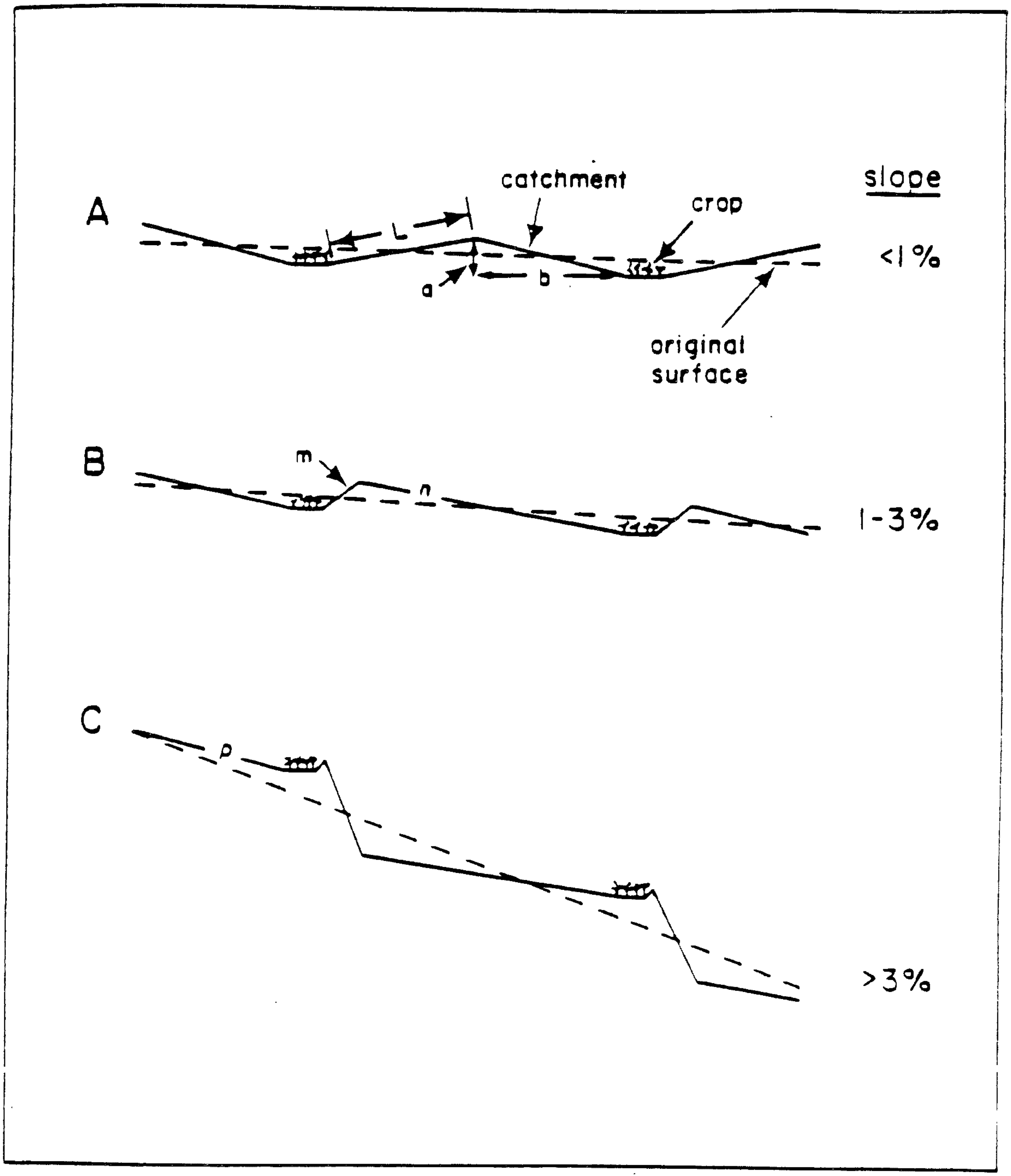


Figure 18. Shapes of micro catchments for various natural slopes

82

construction and maintenance requirements. The natural tendency of some soils to form surface crusts can be used to advantage.

Whether or not a catchment will be treated depends on several factors; among them are natural runoff characteristics, amenability to treatment, land scarcity or value, and cost of treatment per unit of water collected.

The effects of various treatment processes to increase runoff are given in Table 15. Relative costs of construction in the U.S. are also shown in the table; a more detailed discussion is given in the section on economic analyses. Because of costs, the use of treatments more expensive than dispersion of colloids (salt treatment) for crop production is probably not feasible in most locations.

Effect on Water Quality

If the catchment area is treated by the addition of dispersing agents, sealers, or covers, there will be some change in water quality. The effect of such change on crop production (or other water user) must be assessed. Runoff from salt treated catchments is low in dissolved solids; the salt stays with the clay (Dutt and McCreary, 1975). The runoff from an oil-treated catchment showed ether soluble materials of 1.5 parts per million (Laing and Prout, 1975).

Catchment-Cultivated Area Ratio (CCAR)

The catchment area must be some multiple (usually greater than 1) of the cultivated area. The multiple chosen is a function of the quantity of water needed above that supplied by rainfall, the effectiveness of the catchment in producing runoff, and the minimum acceptable probability of receiving a given amount of runoff. The basic relationship to keep in mind is that water available for the crop is equal to rainfall received directly plus runoff from the catchment area plus water supplied from soil moisture and/or reservoir storage.

Where adequate precipitation data to determine probabilities and/or well-defined rainfall-runoff relationships (models) are unavailable, an approximation method may be used to determine the CCAR. If average annual or seasonal rainfall is known for the area in question and for a nearby area where the chosen crop(s) are being grown successfully on rainfall alone or with irrigation, this information can be used to calculate an approximate ratio. The example below will demonstrate.

Say water harvesting is to be used to grow sorghum at the Oracle Agricultural Center (Page Ranch) where rainfall during the sorghum growing season is 170 mm. Irrigated sorghum is grown successfully at that location with about 560 mm of water. Variability of rainfall is quite high. To have 560 mm available, the catchment area must supply a minimum of three times the rainfall. A factor of safety of 2 (to account for rainfall variability) would dictate a runoff/rainfall ratio of 6 to 1. If runoff is 30 percent of rainfall on an untreated catchment, the CCAR must be 20 to 1. Treatment processes to increase runoff would lessen the required ratio by the magnitude of their effectiveness. Salt treatment, for example would increase the runoff to 50 percent of rainfall and reduce the final CCAR to 12 to 1.

Table 15. Summary of catchment treatments to increase runoff

Treatment	Threshold rainfall (mm)	runoff (%)	Life (years)	Cost/Unit Area* ($/m)^2	Problems	Notes
None	--	--	---	--	--	--
Soil surface	3.1	5-22	permanent			
Rock surface[1]		70	permanent		not always available	
Rock clearing			permanent			
Vegetation	--	--	--	--	--	--
Removal	2.7	20-35	5-10	.03-.10	regrowth	
Type change[2]		increased 6%	indefinite			herbaceous cover reduced from 40 to 16%
Rotation[3]		16	permanent		regrowth	
Smoothing	2.3	20-35	5-10	.03-.10	regrowth	
Shaping	2.2	42	permanent		erosion may cause some change	
Compacting		43		.12		
Dispersion of colloids[4]	2.2	50-80	5-10	0.20-0.50		includes all of the above treatments
Repellents[5]	1.2-1.8	95	5-8	0.50-1.00		
Sealing[6]	.5-1.7	50-85	2-5	1.00-2.00	oil spray lasts about 2 years	
Covers	--	--	--	--	--	--
Permeable[7]	.4	2-41	permanent		surface may be eroded away	includes roaded catchments and flat batters
Sealed permeable[8]	.4	85-95	10-20	1.75-2.50		
Impermeable[9]	.03-1.1	60-95	10-20	5.00-20.00		
Buried impermeable[10]		75-95	10-20	1.00-1.75		

* 1983 costs from Frasier (1984)

[1] sandstone rock, slickrock cliffs

[2] shrubs to grass, reduced cover

[3] conservation bench terrace wheat-sorghum-fallow rotation

[4] sodium chloride, sodium carbonate, sodium tripolyphosphate (1 kg/m^2)

[5] silicone, latex

[6] asphalt, fuel oil & kerosene, wax, soil cement

[7] clay, straw, bentonite

[8] [illegible]

In the above example, reservoir storage might be used to reduce the CCAR. Assume that 100 mm of the required 560 mm total to be applied to the crop will come from storage. With reservoir losses of 50 percent, the volume to be put into storage must be 200 mm multiplied by the cultivated area. We have to assume at this point that the excess runoff resulting from the previously chosen safety factor of 2 will be adequate.

Using the same example, we can again calculate the CCAR. The catchment area now needs to supply only 290 mm (560 mm - 170 mm - 100 mm) or about 1.7 times the rainfall. Again using a safety factor of 2, which also assures having excess runoff to put in storage, our runoff/rainfall ratio would be 3.4. With 30 percent runoff the CCAR would be 11 to 1. Salt treatment again would increase runoff to 50 percent and further reduce the final CCAR to 7 to 1. Remember we assumed that 100 mm would be available from reservoir storage. That figure needs to be verified.

When daily rainfall data and probabilities are available, the procedure is to determine the weekly period of greatest deviation between crop needs and expected rainfall of the probability which satisfies the social needs of the area. In other words, a given failure level may be more acceptable by farmers in a country where government programs reduce risk borne by farmers or where risk insurance is available at reasonable rates than in a country where such services are simply not available. The greatest deviation then requires a certain multiplication of rainfall from the catchment area. Treatment processes which increase runoff will reduce the required ratio as will the use of storage.

An absolute guarantee of successful crop production every year is probably not possible for a water harvesting system even with a very large catchment-cultivated area ratio and some reservoir storage. Cost/benefit analysis will determine the upper limit of the CCAR.

Let's look at another design example using the Oracle Agricultural Center (for which good probability data are available) and sorghum production. We decide that 80 percent probability of success is acceptable by local farmers after interviewing several of them. This means that crop failure is likely in one year out of every five, but since some production will be obtained with less than optimum water, we use rainfall of 50 percent probability as our base. We next compare the weekly water requirement of sorghum at Page Ranch and the rainfall which can be expected to occur with 50 percent probability. (Figure 12) The greatest deviation is seen to occur at week 7 when water needs are 56 mm and rainfall is 11 mm. The minimum CCAR is calculated as follows:

$$\text{CCAR} = (\text{need} - \text{rainfall})/\text{runoff}$$

For an untreated watershed at Page Ranch, runoff is 30 percent of rainfall of this magnitude (11 m) or 3.3 mm and thus the untreated CCAR is

$$\text{CCAR} = (56 - 11)\ 3.3 \cong 14.$$

Runoff from a salt-treated catchment is 50 percent of rainfall, reducing the CCAR to about 8 to 1.

Now we can make a water budget analysis of our system to check the validity of the proposed CCAR. The procedure is as follows:

1. Prepare a table for the analysis (See Table 16).

2. List the weekly crop water requirements (column 2) and weekly average rainfall (column 3) (For Page Ranch this is approximately the same as the 50% probability rainfall.)

3. Calculate and list the weekly runoff (Column 4). Runoff = rainfall x CCAR x collection efficiency (runoff/rainfall). In this example our CCAR is 8 and with a salt treated watershed, collection efficiency is 0.5 (50 percent).

4. Calculate and list the soil moisture change (column 5). Soil moisture change = rainfall + runoff - crop water requirement.

5. Calculate and list the available soil moisture (column 6). This is the accumulation of the soil moisture changes. In this example we have assumed that the soil zone can hold a maximum of 200 mm.

6. Calculate and list the excess runoff (column 7). Excess runoff = available soil moisture for previous period (column 6) + soil moisture changes (column 5) - 200 mm (maximum soil moisture storage).

Our proposed CCAR of 8 seems to be adequate because there were no periods of soil moisture deficit. Keep in mind that in years of less than average rainfall, there could be periods of plant stress, and for years of very low rainfall, crop failure may occur. In addition to assuming that we'll get average rainfall, our analysis also assumes 1) that rainfall and runoff occur at such rates that all will infiltrate and 2) that all moisture stored in the soil is useable by the plants (up to the 200 mm estimated capacity of the soil root zone).

In this example, reservoir storage cannot be used to reduce the CCAR because the budget analysis showed there was no excess runoff to put in the reservoir during the growing season. A different crop and a different rainfall pattern would give different results.

Review Storage Requirement

If after going through the above calculations the catchment-cultivated area ratio seems unusually high (greater than 10) or if there is a particular period in the crop cycle of unusual water deficit, the storage requirement can be reconsidered. A little additional storage might reduce considerably the CCAR required. Where cost of catchment area including treatment and cost of reservoir construction and operation including loss reduction are known, the comparison of increasing the catchment-cultivated area ratio vs. increasing reservoir capacity can be carefully evaluated in making a decision (Frasier, 1975). But there has to be some excess runoff from the system to put in storage.

Remember that avoiding failure of a water harvesting system for years of very low rainfall is seldom cost-effective.

Table 16. Water Budget Analysis for Micro Catchment Design

(1) Weeks After Planting	(2) Crop Water Req.	(3) Avg. Rainfall	(4) Runoff (salt treated, CCAR = 8)	(5) Soil Moisture Change	(6) Available Soil Moisture*	(7) Excess Runoff
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
-1	0	3	12	+15	15	
0	0	6	24	+30	45	
1	3	9	36	+42	87	
2	11	11	44	+44	131	
3	23	11	44	+32	163	
4	35	12	48	+25	188	
5	46	12	48	+14	200	2
6	57	11	44	- 2	198	
7	67	11	44	-12	186	
8	65	10	40	-15	171	
9	59	9	36	-14	157	
10	51	7	28	-16	141	
11	44	6	24	-14	127	
12	33	6	24	- 3	124	
13	25	7	28	+10	134	
14	19	8	32	+21	155	
15	13	10	40	+37	192	
16	9	10	40	+41	200	33
17	5	10	40	+45	200	45
18	1	8	32	+39	200	39
TOTAL	566	168	672	---	200	119

* Maximum assumed = 200 mm

Catchment Area Dimensions

With the given CCAR, the size of the catchment area now can be calculated. Shape is then determined, in part by the shape of the cultivated area; the two areas must be compatible at a common boundary, if one exists. Where water is conveyed between the catchment and the cultivated area through a ditch or canal, the shapes are independent.

The maximum width of catchments (distance from top to bottom along maximum slope) should be limited to avoid excessive erosion. Maximum widths for various slopes and rainfall rates are shown in Table 17.

Reservoir Loss Reduction

Losses from reservoirs are by seepage and evaporation. Seepage and evaporation can be reduced by the methods discussed in Chapter 2.

Reservoir Dimensions

With the principles of loss reduction in mind and a given volume established as most appropriate for the system, the reservoir dimensions can be calculated. Depth should be the maximum practical for local conditions, and the shape should be circular, square, or, if compartments are used, they should be squares. The least cost excavated reservoir is in the shape of an inverted, truncated pyramid. If the reservoir is to be covered to reduce evaporation loss, other shapes may have an economic advantage.

Excess Runoff

Provisions must be made to discharge excess runoff, both from the cultivated area and from the reservoir, if one is used. A spillway can be constructed in the dike surrounding the cultivated area or on the wall of the reservoir. The spillway surface should be lined or treated in some way to minimize erosion.

Design Process Review

The entire micro catchment design process should be reviewed at this time to see if improvements can be made to increase effectiveness, decrease costs or simplify operation and maintenance of the system. Preliminary layout plans or sketches should be made and studied to be sure that nothing has been overlooked.

Micro Catchment Construction

In constructing micro catchments, one must be concerned with the catchment area, conveyance channels, if used, the cultivated area, and a reservoir and pumpback system, if they are included.

Catchment Area. Staking out of the contours proceeds downslope below the protective structures. The contour lines are staked at 20 cm intervals but closer spacing of some intermediate stakes may be needed where rills or ridges cause sudden changes in the alignment. After each contour line has been laid out, its alignment should be checked before the next contour is established. Sections of contour lines can be re-aligned if necessary, to obtain a better

Table 17. Maximum recommended width of catchments for various slopes and rainfall rates.

Rainfall	Slope (%)			
mm/hr	1	3	5	10
	Catchment width (m)			
50	28.8	16.6	12.9	9.1
100	14.4	8.3	6.4	4.6
200	7.2	4.2	3.2	2.3
300	4.8	2.8	2.1	1.5

Source: Shanan and Tadmor, 1979

layout but if such changed are extensive, the design should be re-examined and improved before continuing. Contour lines can be differentiated from each other by flagging them with different colored materials.

The axes of rectangular, square or rhombic patterns are staked out first, one running cross-slope and the other down slope. Accuracy of the layout is dependent on the base lines, and they must be carefully staked. A grid is established in the field by staking out lines parallel to the two base lines using a transit and a tape. The grid can be numbered and lettered so that the location of each stake is cross-referenced with the map.

Plowing may be required to bring clay to the surface for some catchments.

Border ridges in micro catchments are small--about 7 to 12 cm in height and 30 to 50 cm in width - but large enough so that animals and people crossing the ridges and animals burrowing in them do not reduce their original height unduly. Ridges are constructed with a small single-blade plow or furrower. Where borders meet, hand labor is required to close openings made by the blade of the plow (Shanan and Tadmor, 1979).

After staking out the cultivated area, its position must be checked in relation to the micro catchment. Small elevation differences of as little as 5 cm may cause water to collect and concentrate at the wrong end of a micro catchment plot so it is leveled with the aid of a surveyor's level.

Basin size is determined by the design requirements. Smaller basins can be constructed by land labor, but basins larger than 3m x 3m usually are shaped and constructed with a bulldozer.

The excess earth is deposited and spread down-slope on the border ridges. Basins should be constructed before the ridges so that the equipment moving over the area does not destroy or damage the ridges. Depressions made by the tracks of equipment tires are filled in by hand. Basins are shaped by hand labor to inverted truncated pyramid form.

The runoff area for micro catchments is prepared by clearing, smoothing, shaping, compacting, treating with salt or other chemicals, or covering as specified in the design. Much can be done with hand labor and simple tools. Tractors and farm implements or bulldozers may be used if available. Special equipment such as vibrating compactors and rock pickers have been developed for other purposes but may be useful for constructing water harvesting facilities.

Clearing the land by removing rocks and vegetation can be done by hand or machine. Rocks can be used in building dikes or drop structures.

Land smoothing and shaping likewise can be done by hand or machine. Simple land "floats" can be constructed and pulled by hand or animal power. Road graders, bulldozers, and tractors with blades can be used.

Runoff strips and contour terraces often are constructed with a motor grader. The quality and speed of construction depends on the ability of the operator to manipulate the equipment skillfully.

Motor grader blades are reversible, and soil can be moved either to the left or to the right, irrespective of the direction of travel. The depth and width of cut is dependent on the power of the equipment and the hardness of the soil. The angle of the blade is adjusted to keep earth rolling transversely and not just sliding ahead. In contour strips and bench terrace construction earth is moved in one direction only (down slope) while in the construction of strip collectors earth is moved in two directions. The quantity of soil to be moved in each system will depend on design dimensions, soil type and operator experience.

Compaction of a catchment area can be done with hand raking, tampers or small rollers. An automobile can be driven back and forth over the area. Large vibrating drum rollers are suitable if available. Effective compaction is done when soils are moist, either following a rain of at least 10mm or sprinkling by hand or water truck.

Salt treatment is applied by hand or with a fertilizer spreader or similar equipment after the land has been cleared, smoothed and shaped, but before compaction. The use of salt treatment is determined by the amount and type of clay in the soil. (See Table 18) Salt application of 11 tons per ha is also effective for soil sterilization to prevent weed growth.

Salt is mixed into the upper 3 - 5 cm of soil by hand raking or with equipment such as a rototiller or rotary rock rake or can be left on the surface to be washed down by the first rain. Caution: If the rain is heavy, the salt may be flushed away and end up in the wrong place! Following the first rain of at least 10mm the salt treated soil is compacted as previously described. Runoff water which initially may contain salt, must be prevented from entering the cultivated area until the catchment is stabilized. This can be accomplished by temporary diking or covering the cultivated area with a thin plastic sheet which will be removed later. Stability is achieved in one year for catchments constructed with machinery. Those constructed largely with hand labor may require 2 rainy seasons.

Use of wax treatment and coverings of plastic, rubber, asphalt, fiberglass, and combinations of those and other materials for micro catchments are described in other publications (Cooley, et al, 1976; Fink, et al, 1973; Cluff, 1971; Cluff, 1975; National Academy of Science, 1974; Myers and Frazier, 1974; Frobel and Cluff, 1976; and Myers, et al, 1967.) These treatment methods usually are too expensive for production of agricultural crops. They may be economically viable for household and animal water supplies.

Cultivated Area. The cultivated area is laid out and staked. Then it is leveled or shaped. Finally, it is treated as appropriate to increase infiltration, reduce evaporation, and increase water storage and availability in the root zone. In many cases this means doing the same things farmers are doing in their fields nearby. In other cases, soil amendments will be added, mulches will be placed on the surface and soils will be subjected to special treatments and/or mixing to increase water storage and availability. As noted previously, protecting the cultivated area from salty runoff will be necessary on salt-treated catchments until the catchment treatment and stabilization are completed.

Table 18 Salt Application Rates

Principal Clay Type	Percent Clay*	Application Rate**
		tons/ha
Montmorillonite	10 to 20	11t/ha
Illite	> 20	11t/ha
Kaolinite	> 20	11t/ha

* Soils with values less than those shown are not recommended for salt treatment

** NaCl

An overflow area (spillway) is constructed at the lowest point on the dike surrounding the cultivated area to discharge excess water without damaging the dike. The dike is strengthened at that point by use of clay, soil cement, or rock.

Reservoir and Pumping System. The reservoir, if used, and pumping system for micro catchments are constructed using the techniques described in the section entitled, Other Facilities, later in this chapter.

Micro Catchment Example

A micro-catchment water harvesting system has been installed at the Oracle Agricultural Center. It is used for research, teaching and demonstration.

Description of area. An area of about 8 ha was available on land with a 1-2 percent slope. The soil is a Whitehouse gravelly loam up to 150 cm deep. The vegetation was primarily annual and perennial grasses and forbs, and trees and shrubs, dominated by mesquite (Prosopis juliflora) and burroweed (Haplopappus tenuisectus). The average annual rainfall is 370 mm. The land was heavily grazed until 1930 but has not been regularly grazed since then. Grass fires occur infrequently from lightning associated with summer thunderstorms.

Design criteria. The following criteria were used in designing the initial 1 ha water harvesting system:

Crop selection - wine grapes, 2.4 m spacing
Cultivated area shape and dimensions - linear strip, 1.2 m x 120 m
Cultivated area treatment - soil sulfur added, 1 kg/m^2, for pH control
Soil water storage potential - 300 mm
Water required from catchment and reservoir - 850 mm
Reservoir storage need - high, for extremely dry period in May and June, 325 m^3 capacity reservoir, sides and bottom treated with salt, 11 MT/ha
Crop selection review - appropriate crop, drought tolerant
Catchment area type - salt treated, 11 MT/ha, smoothed, compacted
Effect on water quality - some initial increase in salt content expected
Catchment area - cultivated area ratio calculation - 13:1
Storage requirement review - initially adequate, later another reservoir was added
Catchment area dimensions - 7.6 m x 120 m
Excess runoff provisions - unlined channel to reservoir
Supplemental irrigation - 5hp pump, plastic lines, individual mini spray heads
Design process review - the original design was reviewed and judged adequate.

Operation showed more excess runoff was available than had been estimated.

Some Special Systems

There are several special systems of water harvesting which are worthy of mention here. They are modifications or adaptations of the major types.

Modified Furrows

Ordinary furrows can be slightly modified to increase water availability for row crops as the smallest example of a linear strip micro catchment. Spacing of rows is wider than usual for the particular crop with the furrow cross-section shaped to direct runoff toward the plant row. (Figure 19) Modified furrows can be constructed with plows specially adapted for that purpose. (Figure 20) This system is in use in Mexico (Anaya Garduno, 1981) and in Northeast Brazil.

Buried Membranes

Plastic sheeting buried under sandy soil in Israel with rainfall simulation (artificial rain) showed good performance for slopes of 10 percent or greater and an excavated center channel of 20 x 20 cm. (See Figure 21) Runoff efficiency averaged 51 percent (Shanan, et al, 1981). Drainage must be adeuate to avoid salt buildup.

Roaded Catchments

Roaded catchments are used in Australia to increase runoff and direct it to reservoirs for later use (Laing, 1981). This system, which derives its name from its similarity in appearance to roads through isolated areas of Australia, depends on having a clay soil at or near the surface (Figure 22).

Spread-Bank Dams

This system of water harvesting, also referred to as flat-batter dams, provides a catchment surface and reservoir in one unit (Laing, 1981). The catchment and reservoir are provided with a clay surface for minimum infiltration and seepage loss. (Figure 23)

Other Facilities

Reservoirs

Reservoir construction also starts with layout of the design plan and staking. Small reservoirs can be excavated by hand or with simple machinery. If a compartmented reservoir is used, the different sections are constructed in the same way. Sump construction and placement of distribution system piping and that required between compartments is the next step. The sump is hand dug or mechanically excavated as appropriate. If lining is specified, it should be placed quickly after excavation to avoid wall collapse. Special treatment may be specified to reduce seepage and evaporation losses. Detailed reservoir treatment methods have been described by Reginato, et al. (1968).

Seepage Control. When used for reservoir seepage control, sodium salts are applied at the prescribed rate and mixed thoroughly with the top 5 cm of soil. The mixture is moistened to near field capacity and compacted by hand or mechanical tampers.

Polymeric sealants are applied to existing reservoirs by adding approximately one liter of sealant to one thousand liters of stored water. New or emptied reservoirs are treated by moistening the soil surface to a depth of 150 to 30 cm with water containing the polymeric sealant in a 1:1000

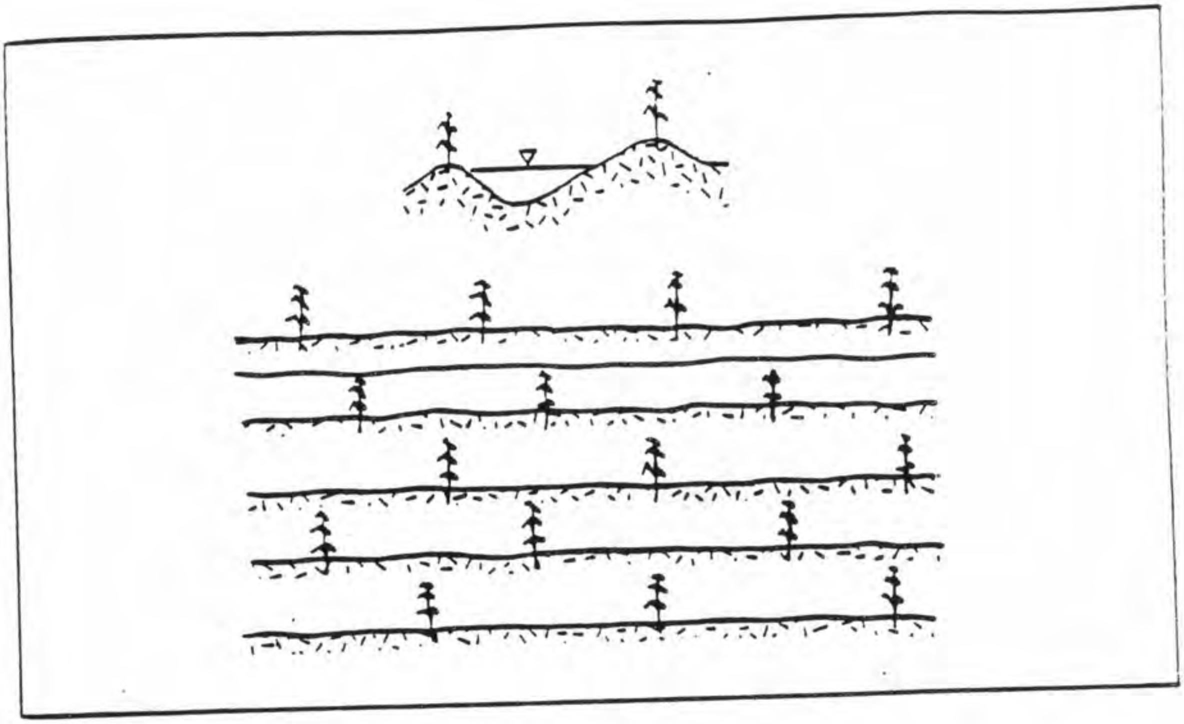


Figure 19. Cross section and artist's conception of modified furrows.
Source: Anaya Garduno, 1981

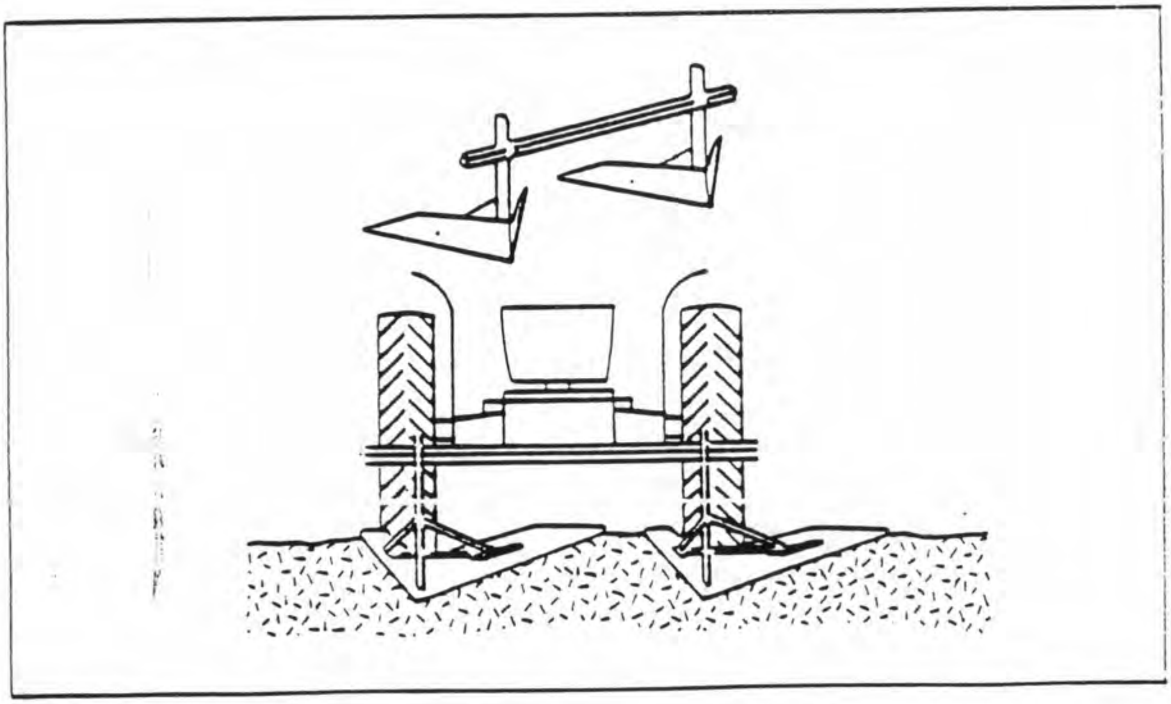


Figure 20. Plow adapted for construction of modified furrows.
Source: Anaya Garduno, 1981

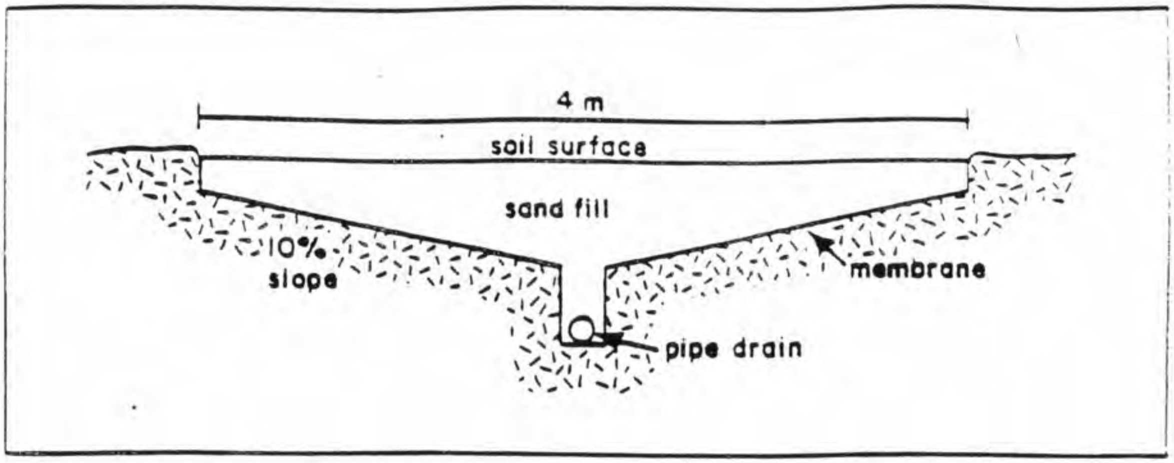


Figure 21. Buried membrane collector.
Source: Shanan, et al. 1981

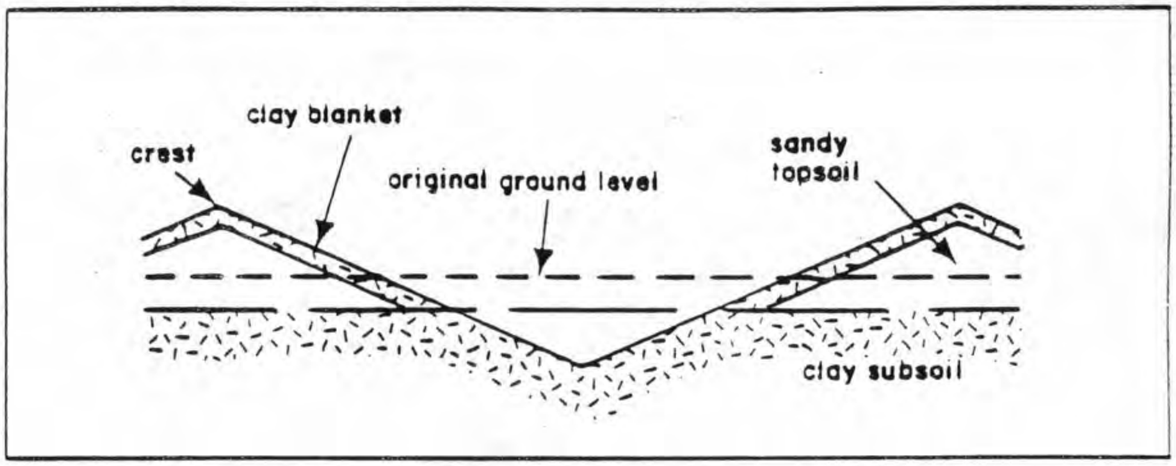


Figure 22. Cross section through adjacent roads in a roaded catchment.
Source: Laing, 1981

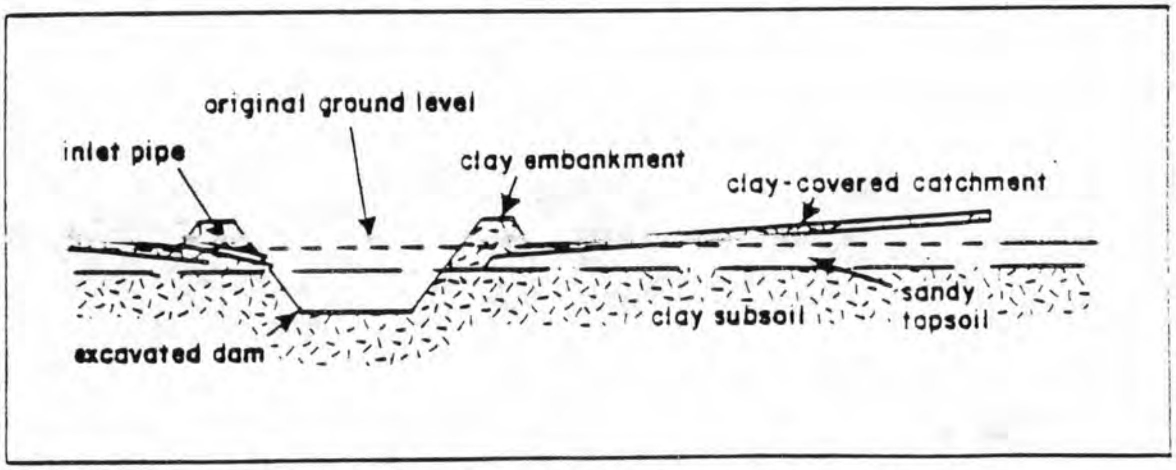


Figure 23. Cross-section through a spread-bank dam and one side of its catchment.
Source: Laing, 1981

volumetric proportion and then compacted (Boyer and Cluff, 1972). Tests should be made with the particular soil to determine the effectiveness of the treatment.

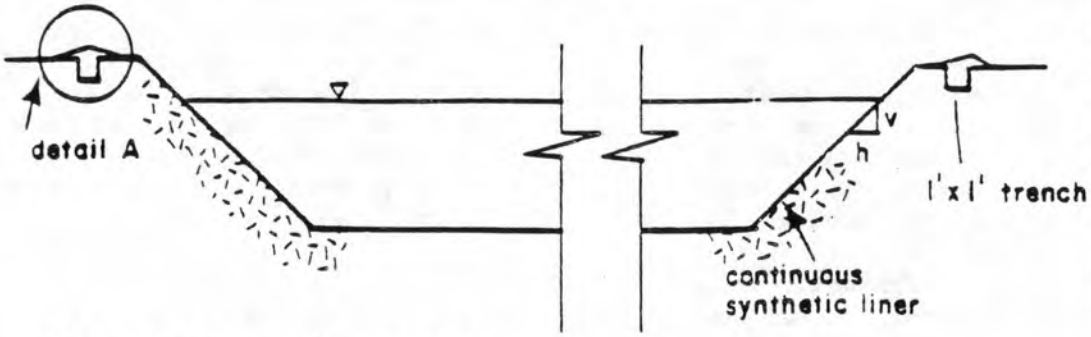
Bentonite clay in the prescribed proportions is mixed with the soil or applied as a layer of pure clay either buried or left on the surface. When soil cement is specified for seepage control, the desired soil type must be available at the site, or a source location must be found that has suitable soil. The top 1.5 to 2 cm of soil at the site first are tilled mechanically. Portland cement is then proportionately distributed and mixed into the soil by hand or with a rotary tiller and, at the same time, water is added to obtain an optimum moisture content. The mixture is then compacted by hand tampers, small rollers, or rubber-tired road compactors or trucks until the finished thickness - usually 2 to 3 cm is obtained. The soil cement must be allowed to cure for up to seven days while being sprayed periodically with water. A central mixing plant can be set up for large projects.

Synthetic membranes for seepage control are easily installed. (See Figure 24) The subgrade is first cleared of sharp aggregate and vegetation and smoothed. Sheets of material are laid down with 10 - 15 cm overlap. Care must be taken in sealing the overlap joints. Mastic and tape are generally used for sealing polyethylene. PVC, chlorinated polyethylene and butyl or hypalon rubber can be seamed with solvent-thinned cements. The earth cover of at least 10 cm thickness is then applied. Detailed construction techniques for synthetic liners may be found in the publication, American Society of Agricultural Engineers EP 340 (1980).

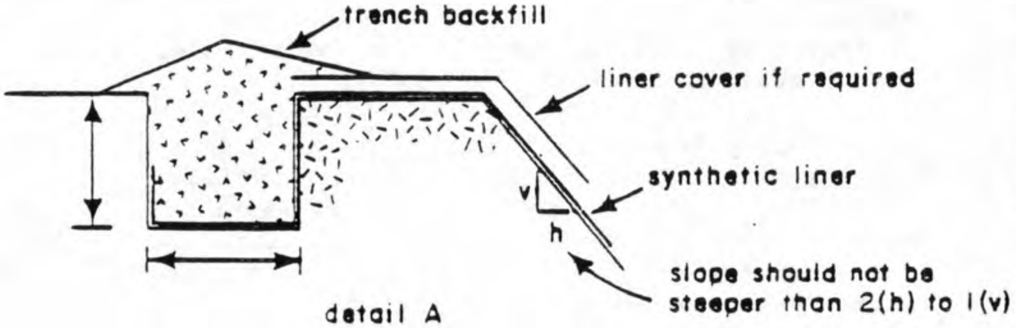
Concrete linings for seepage control are reinforced with wire mesh and generally are poured 5 to 10 cm thick. A small batch plant or locally available ready-mixed concrete would be desirable. Skilled labor and special equipment should be used if available. After pouring, the concrete should be well cured for at least 2 days to help obtain the water tightness and resistance to weathering desired.

The reservoir side walls and bottom are smoothed and properly compacted to grade. The equipment and methods used will depend on the characteristics of the subgrade soil. Expansive subgrade soils should be avoided in colder regions because of damage by frost action. Detailed construction specifications can be obtained from the Portland Cement Association (1962).

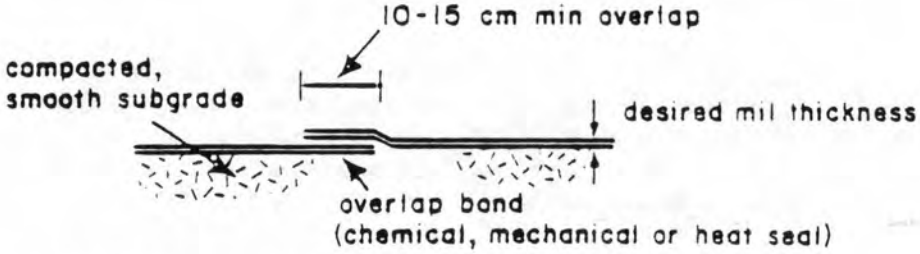
When installing reinforced mortar-covered plastic for seepage control, the polyethylene or polyvinyl is laid down first in overlapping sheets. The plastic must be properly sealed at the overlaps since some cracking in the mortar does occur. Plastic, wire mesh-reinforcement and mortar are all run continuously into an anchor trench at the top of the reservoir slope to prevent slippage of the liner on the slope. The mortar is added in sufficient thickness to cover the wire mesh. Generally an average of 2 cm is used to cover 20 gage stucco wire with 25 mm mesh size. Larger openings increase the difficulty of keeping the wire buried in the cement mortar. With a mesh up to 20 mm, mortar can be dumped on the surface and spread with rakes. Only a light trowelling is required, thus reducing the amount of hand labor needed. Fewer cracks occur when using coarse, washed concrete sand than with fine plaster or mortar sand (Cluff, 1975).



Typical reservoir section



Anchor trench for synthetic liners



Overlap bonding detail

Figure 24. Synthetic Sheet Lining Construction Details
Source: Cluff and Frobel, 1978

The mortar-covered plastic membrane liner can be installed using only hand labor with a minimal amount of equipment. The mortar can also be applied using spray equipment.

The amount of asphalt membrane material required for seepage control will vary with the type of subgrade but will not be less than 7 L/m^2 applied by conventional spraying techniques. When applying asphalt without reinforcement, the lining is covered with soil of sufficient depth to prevent atmospheric degradation or mechanical damage. Fine cover materials, such as sand, are applied directly on the asphalt and then coarse grained gravel or cobbles are added for reservoir banks.

Either anionic or cationic asphalt emulsions can be applied on fiberglass matting by spraying or with industrial floor brooms with soft bristles. Cutbacks (solvent based) usually have to be heated to 65°C minimum and applied by spraying. If spraying, a 1 L/m^2 tack coat is first applied, followed by the 0.025 to 0.033 kg/m^2 fiberglass matting. An additional 2 L/m^2 of asphalt is then applied over the matting.

If brooms are used, the tack coat is not applied, but rather the fiberglass is placed directly on the ground and asphalt is spread across it with the broom. A seal coat of asphalt-clay roofing emulsion then is applied a few days later at a rate of approximately 1.5 L/m^2.

The asphalt is applied at approximately 2 L/m^2. In addition, it is also necessary to seam the joints by placing mastic between the overlapped plastic sheeting.

Asphalt concrete lining is placed by standard paving machines and by special equipment or hand methods on side slopes. Care must be taken to insure proper subgrade preparation and mix as specified.

Evaporation Control. Construction of compartmented reservoirs was described above in the general section on reservoir construction.

Filled reservoirs are excavated, lined, if necessary, and filled with uniformly graded sand, gravel, or rock. These materials are obtained locally or hauled in by truck.

Paraffin wax with a low melting point is applied in chip form and allowed to melt in the hot summer sun to form a continuous floating cover. Floating rafts require only minimal training of unskilled labor for installation. Polystyrene is cut into 1.2 m x 1.2 m squares and impregnated with wax. The sheets can either be clamped together using sections of PVC pipe or connected with straps of butyl or hypalon rubber. Use of the straps will make it possible to accordion-fold the waxed sheets so they can be quickly deployed in times of drought or be easily stored during periods of excess rainfall. Both types of connectors can be used on larger reservoirs provided some type of wave energy dissipation is used to protect the outer perimeter of the system.

A low-cost cover made of locally available materials can be suspended over the water surface. An example is on a tank at Radisele School, Botswana (Ionides, et al, 1969). The tank is covered with sorghum stalks tied together in bundles and supported by steel wire. Inexpensive plastic covers, such as polyethylene or vinyl, are anchored on the sides of the reservoir. Reinforced butyl rubber can be suspended by plastic hose-covered cable. The cable is tied down by buried reinforced concrete anchors. The edge of the rubber is buried in a trench along the edge of the tank (Cluff, 1971).

Rigid roof structures made of steel or concrete are constructed on site or shipped as a prefabricated package. They require skilled labor and suitable tools for erection.

Reservoir spillways are constructed using the techniques previously described for conveyance channel or terrace spillways.

The reservoir should be fenced for safety.

Pumpback systems

If a reservoir is used, and it is located below the cultivated area, a system for pumping and distributing the stored water back to the cultivated area is required. Pumps can be powered by humans or animals, by wind, or by small diesel or gasoline engines. When a windmill is used, some information about wind characteristics must be obtained. Particularly important is the availability of reliable winds during the driest period of the crop cycle. A pipeline or hose is required to return the water to the high point in the system. Subsequently it can be distributed by gravity on the surface or through additional pipes or hoses. Or it can be distributed directly from the pump. Trickle irrigation techniques may be used. The pump should be selected on the basis of the maximum lift required and desired flow rate. A floating pump can be used, but a fixed installation may be easier to operate and maintain.

For fixed installations a sump will be required; it can be located in the side wall of the reservoir or a short distance away. A sediment trap or filter or screen can be used to prevent sand from entering the pump. (See Figure 25) When a sump is used it can be a hand dug open pit if the walls won't collapse or it may be concrete or rock lined. Large diameter plastic pipes or corrugated metal drain pipes make good sumps for small systems. The sump should be large enough to accommodate the pump and to allow for regular cleaning and other maintenance. When hand operated or windmill driven pumps are used, an auxiliary engine-driven pump is a good idea and provisions for its use must be considered in designing the sump and locating the main pump and associated piping.

The pumping system is designed to take water from the reservoir (or from a compartment of the reservoir) and move it to the cultivated area or to another reservoir compartment. The pump should be selected with the capabilities of the people who will operate and maintain it in mind.

The pump should be located conveniently in the reservoir or between the reservoir and the cultivated area. If the sump is separated, pipe connections to the sump must be made from the reservoir (from all compartments if a compartmented reservoir is used) and each inlet must have a control valve.

Pump discharge must be carried to the cultivated area through a hose, pipeline, or combination hose and pipeline distribution network. The water distribution system (pipes, hoses, valves) can be placed on the surface or

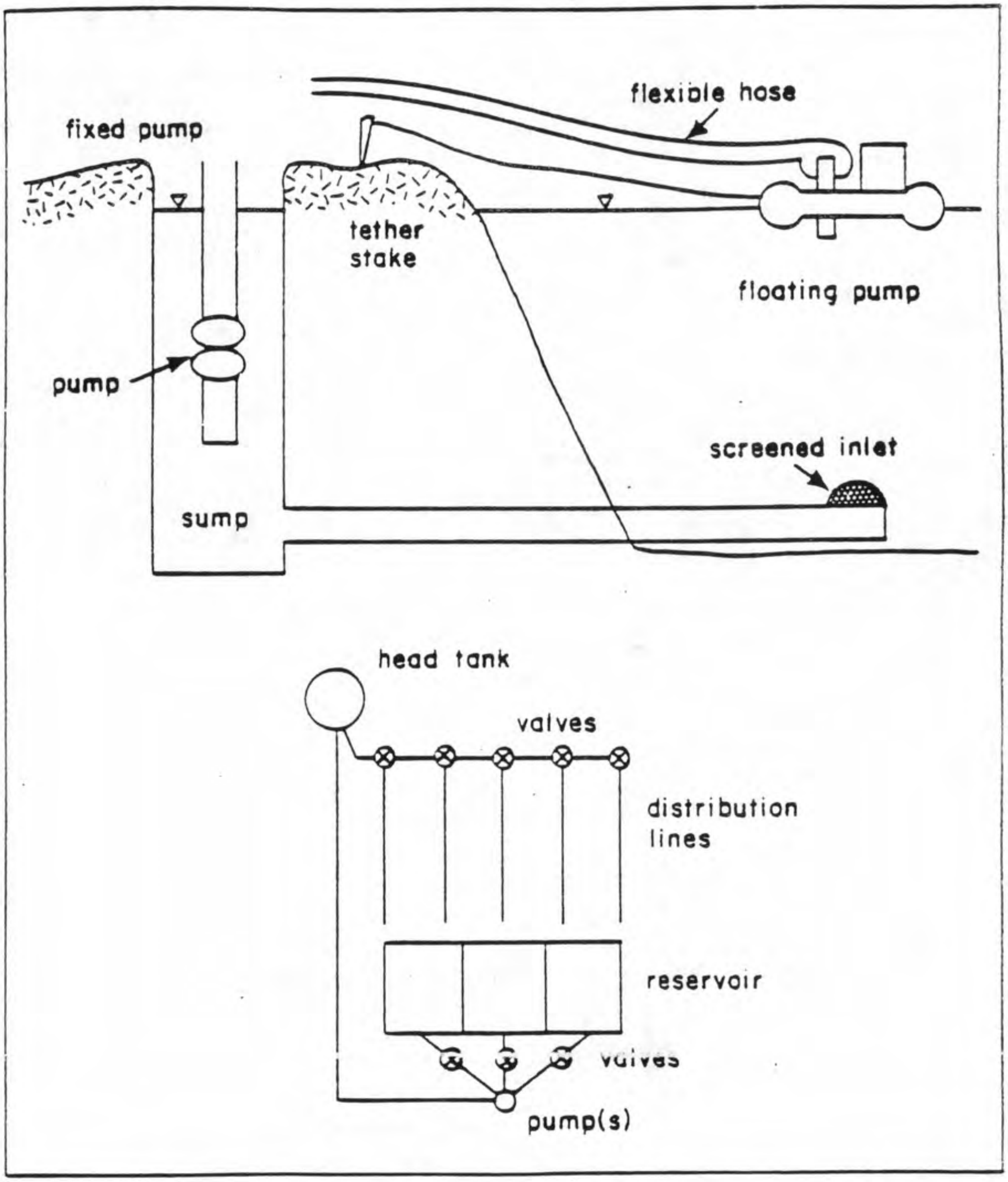


Figure 25. Typical Pumpback System Details

buried. A buried system has the advantage of suffering less damage from traffic (people, animals, or machines) in the area. If freezing weather is expected, provisions must be made for draining an exposed distribution system or the system must be buried below the frost line. Provisions must be made to discharge into the various compartments of a compartmented reservoir.

Both a flow rate (L/hr) and a total lift (m) must be specified in the design. In addition to the actual elevation difference between the bottom of the reservoir and the highest cultivated area, lift includes the friction losses in the distribution system. Pipe sizes should be chosen to keep friction losses low. Hydraulic tables are published giving information on friction losses for different flow rates, pipe diameters and lengths, and pipe materials.

Pump flow rates should be chosen so that the entire cultivated area can receive an emergency irrigation over a 7 to 10 day period. To allow for maintenance and repair time, a motor or engine-driven pump should not be expected to run continuously; a 12 hour on, 12 hour off cycle is reasonable.

Consider the following design example.

Given:

Cultivated area - 2 ha
Reservoir depth - 2 m
Elevation of: highest cultivated area - 400 m
pump location - 375 m

Assume:

Emergency irrigation application - 5 cm
Irrigation cycle - 15 days/12 hrs. per day

Calculate:

Water required = 2 ha x 5 cm = $2 \times 10^4 \times 5 \times 10^{-2} = 1000 m^3$
Pumping rate = $1000 m^3$/15 days x 12 hrs. = $1000 \times 10^3 / 1.8 \times 10^2$ L/hr = 5555 L/hr
Friction loss (from hydraulic tables) for 200 m of 5 cm plastic 5555 L/hr = 5m*
Lift = 2m + (400 - 375) m + 5m = 2 + 25 + 5 = 32m

*If friction loss is more than 10 percent of total lift, a larger pipe size should probably be used.

A pump capable of delivering at least 5555 L/hr at a head (lift) of 32 m would be required. Larger systems will require a larger pump or several small pumps can be used.

Pumping System Construction. The pumping system is laid out and constructed from the design specifications. The pump is mounted on the bank near the sump or in the sump, suspended from a small platform at the surface or from a larger framework if a windmill is used.

Pipes connecting the reservoir to the sump and control valves are installed during reservoir construction. The pump discharge pipe is brought to the surface for connection to the distribution system.

The sump should be provided with a sturdy cover to prevent children and small animals from falling into it.

The distribution system is tested for leaks as soon after installation as water is available and before covering, if a buried system is used.

Instrumentation

The level of instrumentation used in a water harvesting/runoff farming system varies with its purpose. A research facility will require much more instrumentation than an operational installation. In the latter case, a means of measuring (1) rainfall, (2) runoff, (3) soil moisture, (4) reservoir level (if one is used) and (5) pumped water applied would be important. Plastic rain gages, simple flumes and measuring sticks, soil moisture probes (blunt rods), staff gages and calibrated buckets, respectively, could be used to accomplish the above measurements.

Research facilities should have a complete weather station including a recording raingage, evaporation pan, recording relative humidity gage and thermometer, and maximum and minimum temperature thermometers. Solar radiation and wind speed and direction measurements may be important. Atmometers can be used to estimate evapotranspiration. Flumes with water level recorders should be used to measure diverted flow or excess flow from cultivated areas or reservoirs. Soil moisture can be measured with any of the conventional methods such as tensiometers or neutron probes. Water level recorders can be used to monitor reservoir water levels, and water meters (propeller type) will record water applied through a pumpback system.

Costs of Design Alternatives

Cost of alternatives in design are different. Therefore, some design decisions cannot be made effectively in the absence of cost data. For example, it is generally less expensive to improve the catchment area than to reduce evaporation (Laing, 1981). Costs of system construction also will be different in different countries or even at different locations in the same country.

Micro catchment costs vary according to topographic site conditions and layout. Costs of non-chemically treated systems in Israel and Australia range from $100 to $300 per ha (1975 prices). Compaction increases the costs by $100 to $150 per ha. Bitumen covered catchments including site preparation, herbicides, bitumen surfacing and fencing will cost at least $1500 per hectare and may reach $1800 per hectare because of high costs of bitumen (Shanan and Tadmor, 1979).

The unit cost of water in micro catchment systems is a function of catchment construction cost, annual precipitation, runoff efficiency, the life of the system and maintenance costs. In the 100 mm rainfall region of Israel, where runoff efficiency is 15 to 20 percent and the life of the system at least 10 years, unit cost of water is $0.05 to 0.15 per cubic meter (Shanan and Tadmor, 1979).

Labor and material costs can vary greatly throughout the world; Cluff and Frobel (1978) analyzed costs in the United States for labor, materials and equipment, assuming good site conditions for small projects of less than 1 hectare. Costs for small projects can be reduced if several are constructed at the same time.

Table 19 is a comparison of costs of various catchment construction methods.

Analysis of economic feasibility is the final step in the design process. Will the anticipated benefits of the system equal or exceed its costs?

A procedure for economic analysis of water harvesting/runoff farming systems is being developed at the University of Arizona. Preliminary details are given in Chapter 5.

Design Process Review

Because of the complexity of the process, the designer should review completely at this point the steps followed in designing the water harvesting/runoff farming system. In this way the calculations can be improved and made more accurate, and the designer can be assured that nothing has been forgotten.

Table 19. COMPARISON OF CATCHMENT CONSTRUCTION COSTS

Catchment Treatment	Estimated Capital Cost[1] ($\$/m^2$)	Estimated Life (Years)	Estimated Annual Maintenance Costs[2] (Percent)	Estimated Retreatment Costs ($\$/m^2$)	Estimated Average Amortized Costs $\$/m^2$ (20 years)[3]
I Earth Structures					
Land Clearing	0.03	5-10	15	0.01	0.006
Roaded Catchments	0.10	10-15	10	0.03	0.013
II Chemical					
Sodium Chloride	0.14	8-10	5	0.07	0.025
Sodium Carbonate	0.18	6-8	5	0.11	0.044
Wax (paraffin)	0.42	5-10	5	0.32	0.206
III Asphalt					
Fiberglass Asphalt-Chipcoated (FAC)	0.50	10-15	1	0.30	0.081
Asphalt-Plastic-Asphalt-Chipcoated (APAC)	0.75	10-15	1	0.30	0.107
Asphalt Rubber	0.80	10-15	1	0.65	0.143
Asphalt-Concrete (10 cm)	3.35	15-20	0.1	3.35	0.426
IV Synthetic Membranes					
Graveled Polyethylene Plastic	0.60	15-25	1	0.60	0.086
Reinforced Mortar-Coated Polyethylene Plastic	2.10	20-25	0.1	2.10	0.214
Chlorinated Polyethylene	3.50	10-15	1	3.40	0.703
Sheet Metal	3.50	20-25	0.2	3.40	0.356
Artificial Rubber	4.50	10-15	0.2	4.40	0.906

---

[1] Capital costs include estimated labor, equipment and material at 1976 U.S. prices for systems under approximately two hectares in size.

[2] Expressed as a percentage of initial capital costs.

[3] Amortization calculated on minimum life at an annual interest rate of 8 percent. Inflation rates were also assumed to be 8 percent per annum on the retreatment costs.

Source: Cluff and Frobel, 1978

4. OPERATION AND MAINTENANCE

When the water harvesting/runoff farming system is designed and constructed, a set of operating practices will be required. They should be developed as part of the design and construction phases, but will be modified as experience is gained in actually operating the system. Management of these small scale water management systems is more complex than typical rain fed agriculture and requires a higher level of personal attention, particularly during rainfall/runoff events.

Designers and constructors of small-scale water management systems have a responsibility to the people for whom the work is being done to insure successful operation and maintenance. Training of local operating and maintenance personnel will be required as will a stock of repair and replacement materials and parts (Pacey, 1977; and Cotgageorge and Henderson, 1983).

Agronomic practices

The agricultural operation of the system--fertilizer applications, cultivation, weed and pest control must be supervised by a competent agricultural expert if new procedures are involved.

The choice of annual or perennial crops (or both) will be made during the design process. If perennial crops are to be included, they may be planted at the time of construction, if appropriate, or just before the major rainy season. When using micro catchment basins, trees or shrubs are planted at or near the lowest point in the basin. An emergency source of water may be necessary during the first several years in case the rains are late or insufficient because the root system needs time to develop. Planting, fertilizing, cultivation, pest control, and harvesting activities are carried out for water harvesting/runoff farming systems in the same way as for traditional farming systems in the area. Planting date for annual crops will ordinarily coincide with the first rain of at least 3 mm in the appropriate growing season for the crop.

Water management

Water management is crucial; it requires special attention. Observation and control during runoff events is the first step. Operation of gates, dividers, overflow devices and drains must be observed and evaluated. Are they working properly during maximum flow periods?

The operator probably may not be in the field during the first flood because of the erratic nature of the rainfall in regions where water harvesting/runoff farming is most appropriate, but a site visit should be made immediately afterwards to inspect all water control facilities, the catchment and cultivated areas and protective structures. Common defects which appear after the first flood are of two types (Shanan and Tadmor, 1979):

1. Too much water concentrating and causing overtopping. In some cases the runoff flowing towards a weak point can be reduced by leading a part of it to another area, and in other cases the border or embankment height can be raised or spillways can be improved. Dikes may have to be breached to eliminate excess flow.

2. Too little water in part of the cultivated area. The flow to these areas can be augmented by constructing a small furrow to lead runoff to them. Some reconstruction may be required.

The rainfall records of the first flood should be examined. If the rainfall is above average and few breaks occurred, and the system received ample water, the design is satisfactory. If the rainfall was below average, the results are satisfactory if at least 90 percent of all cultivated areas received a reasonable wetting and there were no breaks in the system.

After the first flooding, checking the depth of wetting of cultivated areas with a soil probe is a good practice. On the basis of these observations, the amount of available moisture in the root zone can be calculated and compared to results in other plots (Shanan and Tadmor, 1979).

For systems with capability for it, supplemental irrigation is applied as needed during the growing season. A method of assessing plant moisture stress is needed to assist the farmer/operator in decision making regarding irrigation. When both annual and perennial crops are grown and drought conditions are extreme, the decision involves compromise between trying to get some level of harvestable product from both crops and ensuring survival of the perennial crop.

Water stored in the reservoir is subject to both evaporation and seepage losses whereas putting it into the plant root zones decreases such losses. In general, then, maintaining a high level of soil moisture storage is advisable.

Water usually flows by gravity into the storage reservoir. It is then pumped out of storage for application as described above. When using a compartmented reservoir, the deepest compartment should be kept full at all times. Water is kept in the fewest number of compartments possible by pumping between compartments as water is used.

Maintenance

The success of the project also depends on adequate maintenance. The need for maintenance is related to the type of water harvesting/runoff farming system and to the construction methods used. Routine preventative maintenance is very importance for all parts of a water harvesting/runoff farming system. Some of the maintenance topics to be considered are the following:

- runoff area (for micro catchment systems)--maintain integrity of surface, allow minimum traffic of people and animals, use fencing or guards, carry out weed control or other vegetation control
- conveyance system--weed control, erosion control, seepage reduction, regular cleaning of sediment deposits, repair of surface breaks, repair of diversion and division structures
- cultivated area--dike repair, weed control, plowing or treatment to mix deposited clay and other sediments (particularly in new water spreading systems), pest control (including birds, rodents, insects, fungi and diseases).

- storage reservoir--weed control, sediment removal, elimination of gophers and other burrowing animals. Controlled animal grazing may be used to reduce excessive grass growth in the reservoir area. If reservoirs are covered, the covers will require maintenance.

- pumping system--general mechanical repair; regular, routine preventative maintenance examination, efficiency tests. Clean out sediment, floating debris in sump. Pump breakdown is a major cause of failure of water supply projects around the world (Cotgageorge and Henderson, 1983).

Maintenance of micro catchment systems must be regular, and all breaks require attention. Sediment accumulation in the system should be negligible--except for the first year when erosion occurs at entrances to basins and micro-rills appear on part of the steep slopes. Micro catchment systems cannot be supervised from the office. They require a regular inspection after every rain. Silt in diversion ditches should be removed immediately and embankments strengthened where necessary.

Rodents present a hazard to micro catchment systems. They burrow through ridges and embankments and water flowing through their holes may cause gullies to form. A common maintenance problem in micro catchment systems is the wearing down and destruction of the low ridges and embankments by grazing animals. These sections of the system must be inspected regularly and equipment operators instructed to use machines so as to cause minimum damage (Shanan and Tadmore, 1979).

108

5. EVALUATION

The design of water harvesting/runoff farming systems can be improved by monitoring and evaluating the results of each project. This evaluation should include comparing predicted and actual runoff, determining whether the layout meets the field conditions and whether yields meet expectations. (Shanan and Tadmor, 1979).

Different evaluations serve different purposes, but any evaluation requires accurate measurement of the various factors involved. Among the measurements which must be made (some of them repeatedly) in evaluation are the following (unless they were made during design and construction):

land used - catchment and cultivated area
precipitation - amount and rates
runoff
soil moisture
supplemental water applied
reservoir water level (throughout the year)
plant growth rates
forage, seed or fruit yield

Primary interest is in production per unit of land (harvested output of crop, forage, or wood per hectare) and production per unit of labor. We may also be interested in production per unit of energy, particularly purchased energy, or production per unit of capital and other purchased inputs.

Secondary interest might be in efficiency of water collection, conveyance, and storage.

Evaluation can be separated into technical and economic components.

Technical Components

Efficiency of water collection can be defined as:

$$\frac{\text{water collected (outflow from catchment area)}}{\text{rainfall}} \times 100$$

Efficiency of water conveyance is:

$$\frac{\text{output from conveyance channel}}{\text{input to conveyance channel}} \times 100$$

Efficiency of water storage is:

$$\frac{\text{water supplied from storage}}{\text{water delivered to storage}} \times 100$$

Overall water efficiency is:

$$\frac{\text{water used by plants} \times \text{cultivated area}}{\text{rainfall} \times (\text{catchment} + \text{cultivated areas})} \times 100$$

Economic Components

Water harvesting/runoff farming projects are assessed on their economic rates of return. Arid zone systems are marginal economic enterprises at best because of the extreme variability of the climatic conditions.

In general, microcatchment systems are economically feasible in regions where low cost sources of water are unavailable and where extensive areas would otherwise be sub-marginally used only by grazing, if at all.

Table 20 details the amortized catchment construction costs for various annual precipitation rates per cubic meter of collected runoff. Replacement costs and capital costs were combined as needed to reflect a 20-year life for comparing different systems (Cluff and Frobel, 1978).

Maintenance costs are small in comparison to capital costs.

Economic evaluation requires a comparison of the costs and benefits of water harvesting/runoff farming systems with the costs and benefits of existing and alternative production systems.

Some of the economic factors required to make the evaluation are listed in Chapter 2 and some of the costs involved are given in Chapter 3. Other costs are analyzed in the material following.

Personal income of farm families must be determined.

Social costs and benefits are not easily evaluated and probably should not be, at least in monetary terms. But consideration should be given to changes in such things as:

employment levels
emergency relief requirements (e.g., for food)
work load.

Table 20. WATER COSTS[1] PER UNIT OF RUNOFF FOR VARYING PRECIPITATION

Annual Precipitation

	Range (mm)	100-200	200-300	300-450	400-600	400-850	600-900	600-1200	800-1200
CATCHMENT TREATMENT	Average (mm)	(150)	(250)	(375)	(500)	(625)	(750)	(900)	(1000)
				$/1000 liters			$/1000 liters		
I EARTH STRUCTURES									
Land Clearing		0.28	0.17	0.11	0.08	0.07	0.06	0.05	0.04
Roaded Catchments		0.51	0.31	0.20	0.15	0.12	0.10	0.09	0.08
II CHEMICAL									
Sodium Chloride		0.36	0.21	0.14	0.11	0.08	0.07	0.06	0.05
Sodium Carbonate		0.59	0.35	0.24	0.18	0.14	0.12	0.10	0.09
Wax (paraffin)		2.02	1.21	0.81	0.61	0.48	0.40	0.35	0.30
III ASPHALT									
Fiberglass Asphalt Chipcoated (FAC)		0.60	0.35	0.24	0.18	0.14	0.12	0.10	0.09
Asphalt-Plastic-Asphalt-Chipcoated (APAC)		0.80	0.48	0.32	0.24	0.19	0.16	0.14	0.12
Asphalt-Rubber		1.06	0.64	0.42	0.32	0.25	0.21	0.18	0.16
Asphalt-Concrete		3.01	1.81	1.21	0.90	0.72	0.60	0.52	0.45
IV SYNTHETIC MEMBRANES									
Graveled Polyethylene		0.88	0.53	0.35	0.26	0.21	0.17	0.15	0.13
Reinforced Mortar-Covered Polyethylene		1.65	0.99	0.66	0.50	0.40	0.33	0.28	0.24
Sheet Metal		2.48	1.48	0.99	0.74	0.59	0.49	0.32	0.37
Chlorinated Polyethylene (CPE)		5.04	3.03	2.02	1.51	1.21	1.01	0.86	0.76
Artificial Rubber		6.26	3.75	2.50	1.88	1.50	1.25	1.07	0.94

---

[1] Water costs are based on capital costs, average catchment efficiency, annual maintenance and average 20 year annual amortization at 8 percent interest rate. Water costs do not consider storage losses.

Source: Cluff and Frobel, 1978.

NOTE: These figures should be verified.

APPENDIX A. REFERENCES CITED

American Society of Agricultural Engineers. 1980. Installation of flexible membrane linings. American Society of Agricultural Engineers Engineering Practice: ASAE EP340.1, Agricultural Engineers Yearbook, pp. 476-481.

Anaya Garduno, M. 1981. Research methodologies for in situ rain harvesting in rainfed agriculture. In G.R. Dutt, C.F. Hutchinson and M. Anaya Garduno, eds., Rainfall Collection for Agriculture in Arid and Semiarid Regions. Proceedings of a workshop hosted by the University of Arizona, USA, and the Chapingo Postgraduate College, Mexico. Commonwealth Agricultural Bureaux. pp. 43-47.

Billy, B. 1981. Water harvesting for dryland and floodwater farming on the Navajo Indian Reservation. In G.R. Dutt, C.F. Hutchinson and M. Anaya Garduno, eds., Rainfall Collection for Agriculture in Arid and Semiarid Regions. Proceedings of a workshop hosted by the University of Arizona, USA, and the Chapingo Postgraduate College, Mexico. Commonwealth Agricultural Bureaux. pp. 3-7.

Boyer, D.G. and C.B. Cluff. 1972. An evaluation of current practices in seepage control. Hydrology and Water Resources in Arizona and the Southwest. Arizona Section, American Water Resources Association. Proceedings, Vol. 2.

Branson, F.A., et al. 1981. Rangeland Hydrology. 2nd Edition. Society for Range Management, Denver, Colorado. Kendall/Hunt Publishing Co., Dubuque, Iowa, USA.

Carmona Ruiz, G. and H.A. Velasco Molina. 1981. Rain harvesting for human and livestock consumption in the semidesert high plains of Mexico. In G. R. Dutt, C.F. Hutchinson and M. Anaya Garduno, eds., Rainfall Collection for Agriculture in Arid and Semiarid Regions. Proceedings of a workshop hosted by the University of Arizona, USA, and the Chapingo Postgraduate College, Mexico. Commonwealth Agricultural Bureaux. pp. 77-81.

Cluff, C.B. 1971. Plastic catchments for economical harvesting of rainfall. In Proceedings of the Tenth National Agricultural Plastics Conference, Nov. 2-4. J.W. Courter, University of Illinois, Chicago.

Cluff, C.B. 1975. Engineering aspects of water harvesting research at the University of Arizona. In Proceedings of the Water Harvesting Symposium, Phoenix, Arizona, March 26-28, 1974. Agricultural Research Service, U.S. Department of Agriculture. ARS W-22, pp. 27-39.

Cluff, C.B. 1977. The compartmented reservoir--a method of efficient water storage. Ph.D. Dissertation. Department of Civil Engineering, Colorado State University, Fort Collins, Colorado. 149 pp.

Cluff, C.B. and R.K. Frobel. 1978. Water harvesting catchment and reservoir construction methods. Water Resources Contribution No. 2. Water Resources Research Center, University of Arizona, Tucson. 44 pp.

Cluff, C.B. 1981. Surface storage for water-harvesting agrisystems. In G.R. Dutt, C.F. Hutchinson and M. Anaya Garduno, eds., Rainfall Collection for Agriculture in Arid and Semiarid Regions. Proceedings of a workshop hosted by the University of Arizona, USA, and the Chapingo Postgraduate College, Mexico. Commonwealth Agricultural Bureaux. 23-30 pp.

Cooley, K.R., L.N. Brazell, G.W. Frasier, and D.H. Fink. 1976. Stock-Water Harvesting with Wax on the Arizona Strip, Vol. 6, Hydrology and Water Resources in Arizona and the Southwest, Proceedings of the 1976 Meeting of the Arizona Section, American Water Resources Association and the Hydrology Section, Arizona Academy of Science, April 29 - May 1, 1976, Tucson, Arizona. pp. 291-294.

Cotgageorge, A. and H.K. Henderson. 1983. The potential Social Impacts of Promoting Water Harvesting for Water Supply and Farming Improvements in the Developing World. Prepared for Women in Development Program - Title XII, Office of Council for International Programs, University of Arizona, Tucson, Arizona.

Dedrick, A.R., T.D. Hanson, and W.R. Williamson. 1973. Floating sheets of foam rubber for reducing stock tank evaporation. Journal of Range Management 26(6):404-406.

Doorenbos, J. and W.O. Pruitt. 1977. Guidelines for predicting crop water requirements. FAO Irrigation and Drainage paper 24. Food and Agriculture Organization of the United Nations. Rome, Italy. 144 p.

Dutt, G.R. and T.W. McCreary. 1975. Multipurpose salt treated water harvesting systems. In Water Harvesting Symposium Proc., Phoenix, Ariz. March 26-29. U.S. Dept. Agr., Agr. Res. Serv. ARS W-22, pp. 310-314.

Dutt, G.R. 1981. Establishment of NaCl-treated catchments. In G.R. Dutt, C.F. Hutchinson and M. Anaya Garduno, eds., Rainfall Collection for Agriculture in Arid and Semiarid Regions. Proceedings of a workshop hosted by the University of Arizona, USA, and the Chapingo Postgraduate College, Mexico. Commonwealth Agricultural Bureaux. pp. 17-22.

Dutt, G.R., C.F. Hutchinson, and M. Anaya Garduno, eds. 1981. Rainfall Collection for Agriculture in Arid and Semiarid Regions. Proceedings of a workshop hosted by the University of Arizona, USA, and the Chapingo Postgraduate College, Mexico. Commonwealth Agricultural Bureaux. 97 pp.

Erez, Ammon. 1977. Growing the Peach in a Meadow Orchard System: Data and Prospects after 5 years of Experimentation. Hort. Science. 12:416.

Erie, L.J., O.F. French, and K. Harris. 1968. Consumptive Use of Water by Crops in Arizona. Technical Bulletin 169, Agricultural Experiment Station. The University of Arizona, Tucson, Arizona. 46 p.

Evenari, M.L. et al. 1971. The Negev: The Challenges of a Desert. Harvard University Press, Cambridge, Massachusetts.

Fink, D.H., K.R. Cooley and G.W. Frasier. 1973. Wax-treated soils for harvesting water. Journal of Range Management 26(6):396-398.

Fink, D.H. and W.L. Ehrler. 1981. Evaluation of materials for inducing runoff and use of these materials in runoff farming. In G.R. Dutt, C.F. Hutchinson and M. Anaya Garduno, eds., Rainfall Collection for Agriculture in Arid and Semiarid Regions. Proceedings of a workshop hosted by the University of Arizona, USA, and the Chapingo Postgraduate College, Mexico. Commonwealth Agricultural Bureaux. pp. 9-16.

Flug, M. 1981. Production of annual crops on microcatchments. In G.R. Dutt, C.F. Hutchinson and M. Anaya Garduno, eds., Rainfall Collection for Agriculture in Arid and Semiarid Regions. Proceedings of a workshop hosted by the University of Arizona, USA, and the Chapingo Postgraduate College, Mexico. Commonwealth Agricultural Bureaux. pp. 39-42.

Frasier, G.W., ed. 1975. Proceedings of the Water Harvesting Symposium, Phoenix, Arizona, March 26-28, 1974. Agricultural Research Service, U.S. Department of Agriculture, ARS W-22, 329 pp.

Frasier, G.W. 1975. Water Harvesting for Livestock, Wildlife, and Domestic Use. In Proceedings of the Water Harvesting Symposium, Phoenix, Arizona, March 26-28, 1974. Agricultural Research Service, U.S. Department of Agriculture, ARS W-22, p. 40-49.

Frasier, G.W. 1981. Water for animals, man, and agriculture by water harvesting. In G.R. Dutt, C.F. Hutchinson and M. Anaya Garduno, eds., Rainfall Collection for Agriculture in Arid and Semiarid Regions. Proceedings of a workshop hosted by the University of Arizona, USA, and the Chapingo Postgraduate College, Mexico. Commonwealth Agricultural Bureaux. pp. 83-86.

Frasier, G.W. 1984. Water harvesting, including new techniques of maximizing rainfall use in semiarid areas. Paper presented at Fourth Annual Agricultural Sector Symposium, World Bank, Washington, D.C. 9-13 January. 26 pp.

Frobel, R.K. and C.B. Cluff. 1976. Plastic reinforced asphalt seepage barrier. American Society of Civil Engineers, Journal of the Irrigation and Drainage Division, September.

Hoiberg, A.J. 1965. Bituminous Materials: Asphalts, Tars and Ditches, Vol. II, Part I, Interscience Publishers, New York, NY.

Hollick, M.F.G. 1975. The design of roaded catchments for maximum runoff. In Proceedings of the Water Harvesting Symposium, Phoenix, Arizona, March 26-28, 1974. Agricultural Research Service, U.S. Department of Agriculture, ARS W-22, pp. 201-220.

Humphrey, R.R. and R.J. Shaw. 1957. Paved drainage basins as a source of water for livestock or game. J. Range Mgt. 10(2):59-62.

Ionides, M.G., G. ap Rees, V. Gibberd, P.R. Moody, D.S. Thornton and M. Upton. 1969. The Introduction of Rainwater Catchment Tanks and Micro-Irrigation to Botswana. Intermediate Technology Development Group, London, 74 pp.

Krantz, B.A. 1981. Rainfall collection and utilization in the semiarid tropics. In G.R. Dutt, C.F. Hutchinson and M. Anaya Garduno, eds., Rainfall Collection for Agriculture in Arid and Semiarid Regions. Proceedings of a workshop hosted by the University of Arizona, USA, and the Chapingo Postgraduate College, Mexico. Commonwealth Agricultural Bureaux. pp. 53-59.

Laing, I.A.F. and A.L. Prout. 1975. Bitumen, oil, and clay surfaces on a deep sand to increase runoff from farm "dam" (excavated tank) catchments in Western Australia. In Water Harvesting Symposium Proc., Phoenix, Ariz. Mar. 26-28, 1974. U.S. Dept. Agr., Agr. Res. Serv. ARS W-22, pp. 63-75.

Laing, I.A.F. 1981. Rainfall collection in Australia. In G.R. Dutt, C.F. Hutchinson and M. Anaya Garduno, eds., Rainfall Collection for Agriculture in Arid and Semiarid Regions. Proceedings of a workshop hosted by the University of Arizona, USA, and the Chapingo Postgraduate College, Mexico. Commonwealth Agricultural Bureaux. pp. 61-66.

Lane, L.J. 1980. Transmission Losses. In National Engineering Handbook, Section-4, Hydrology, U.S. Dept. of Agriculture, Soil Conservation Service, Washington, D.C.

Lane, L.J. 1982a. A Distributed Model for Small Semiarid Watersheds. ASCE Journal of the Hydraulics Division, October.

Lane, L.J. 1982b. Notes for short course on Water Harvesting for Agricultural Production. Soils, Water and Engineering Department, University of Arizona.

Linsley, Ray, K., Jr., Max A. Kohler, and Joseph L.H. Paulhus. 1982. Hydrology for Engineers. Third Ed. McGraw-Hill Book Co. New York, 508 pp.

Matias, J. 1983. Climatology of Oracle, Arizona and Page Ranch. Unpublished report; Soils, Water and Engineering Department; University of Arizona.

Mielke, E.A. and G.R. Dutt. 1981. Deciduous tree and vine fruit production using water harvesting techniques. In G.R. Dutt, C.F. Hutchinson and M. Anaya Garduno, eds., Rainfall Collection for Agriculture in Arid and Semiarid Regions. Proceedings of a workshop hosted by the University of Arizona, USA, and the Chapingo Postgraduate College, Mexico. Commonwealth Agricultural Bureaux. pp. 31-37.

Myers, L.E., G.W. Frasier and J.R. Griggs. 1967. Sprayed asphalt pavement for water harvesting. Amer. Soc. Civ. Engin. Proc., Jour. Irrig. and Drain. Div. 93(IR3), Proc. paper 93(3):79-97.

Myers, L.E. and G.W. Frasier. 1974. Asphalt-fiberglass for precipitation catchments. Journal of Range Management 27(1):12-15.

Myers, L.E. 1975. Water harvesting 2000 B.C. to 1974 A.D. In Proceedings of the Water Harvesting Symposium, Phoenix, Arizona, March 26-28, 1974. Agricultural Research Service, U.S. Department of Agriculture. ARS W-22, pp. 1-7.

Nabhan, G.P. 1979. The ecology of floodwater farming in arid southwestern North America. Agro Ecosystems. 5:245-255.

National Academy of Sciences. 1974. More water for arid lands. National Academy of Sciences, Washington, D.C. 152 pp.

Oron, Gideon, Jiftah Ben-Asher, Arie Issar and Theo M. Boers. 1983. Economic Evaluation of Water Harvesting in Microcatchments. Water Resources Research 19(5):1099-1105. October.

Pacey, A. 1977. Technology Is Not Enough: Provision and Maintenance of Appropriate Water Supplies. Aqua, 1(1):1-58.

Portland Cement Association. 1962. Concrete for Hydraulic Structures, CB6-2, Chicago, Ill.

Portland Cement Association. 1968. Soil cement linings for water reservoirs. Los Angeles, California.

Porto, Everaldo R. 1982. Centro de Pesquisa Agropecuaria de Tropico Semi-arido (CPATSA), Petrolina, Pernambuco, Brazil. Personal communication.

Reginato, R.J. et al. 1968. Sodium carbonate for reducing seepage from ponds. WCL Report No. 7. U.S. Water Conservation Laboratory, Agricultural Research Service, Phoenix, Arizona.

Rollins, M.B. and A.S. Dylla. 1970. Bentonite sealing methods compared in the field. Journal of the Irrigation and Drainage Division, Proceedings American Society of Civil Engineers, 96(IR2):193-203.

Roth, Robert L. 1983. Soils, Water and Engineering Department; College of Agriculture; The University of Arizona, Tucson. Personal communication.

School of Renewable Natural Resources. 1982. Comprehensive Planning for Strip Mine Reclamation in Dry Regions with Emphasis on Water Harvesting. Final Report to Bureau of Mines, U.S. Dept. of Interior. School of Renewable Natural Resources, University of Arizona, Tucson, Arizona.

Shanan, L. 1975. Rainfall and runoff relationships in the Avdat Region of the Negev Desert. Ph.D. thesis, Hebrew University, Jerusalem, Israel.

Shanan, L. and N.H. Tadmor. 1979. Micro-Catchment Systems for Arid Zone Development. Hebrew University, Jerusalem and Center of International Agricultural Cooperation, Ministry of Agriculture, Rehovot, Israel.

Shanan, L., Y. Morin and M. Cohen. 1981. A buried membrane collector for harvesting rainfall in sandy areas. In G.R. Dutt, C.F. Hutchinson and M. Anaya Garduno, eds., Rainfall Collection for Agriculture in Arid and Semiarid Regions. proceedings of a workshop hosted by the University of Arizona, USA, and the Chapingo Postgraduate College, Mexico. Commonwealth Agricultural Bureaux. pp. 67-76.

Soil Conservation Service. 1972. Hydrology. Section 4, National Engineering Handbook, Soil Conservation Service, USDA, Washington, D.C.

Thornthwaite, C.W. and J.R. Mather. 1957. Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance. Publications in Climatology X:3, Drexel Institute of Technology, Laboratory of Climatology.

Zeller, M.E. 1979. Hydrology Manual for Engineering Design and Flood Plain Management Within Pima County, Arizona. Pima County Dept. of Transportation and Flood Control District, Tucson, Arizona, USA.

APPENDIX B. GLOSSARY

agronomic practices - Those practices carried out by farmers in growing a crop.

arid environment - A region of low rainfall, frequently inadequate to support crop production.

aspect - The direction toward which a sloping land area faces.

berm - A ledge or shoulder as along the edge of a canal or ditch.

canal - An excavated channel for conveying water.

clay - Disperse systems of the products of weathering in which secondary mineral particles smaller than 2 microns predominate.

climate - The average condition of the weather at a place.

concentration point - The single geographic location at which all surface drainage from a given area comes together as outflow.

concentration time - The time required for discharge from the most distant point in a drainage area to reach the concentration point.

consumptive use - Evaporation and transpiration from land areas only, excluding evaporation from lakes and reservoirs.

crop, cultivated crop - A plant that can be grown and harvested extensively for subsistence or profit.

crop production - The process of growing plants for subsistence or profit.

crop production functions (of water) - The relationship between the amount of water available to a plant in the growing season and the production obtained.

crop water requirements - A measure of the amount of water required under normal conditions to produce a harvestable crop.

cultivated area - The area where crops are grown.

cultivation - The growing of crops, may also refer to mechanical process of weed removal.

deep seepage - Infiltration which reaches the water table.

depression storage - Water in puddles and small ponds.

discharge - The rate of flow, or volume of water flowing in a stream or conduit at a given place and within a given period of time expressed as liters per hour or cubic meters per day.

dispersion - The process of scattering or spreading from a fixed source.

diversion - Taking water from a flowing stream.

diversion dam - A structure built across a stream channel to raise the water level and thus make diversion easier. May be temporary or permanent.

drainage area - An area whose runoff is more or less separate from the runoff for adjacent areas, so that it can be considered a hydrologic unit.

drainage basin - drainage area

drainage divide - The boundary line, along a topographic ridge or along a subsurface formation, separating two adjacent drainage basins.

drainage pattern - The overall pattern of major and minor stream channels in a region.

effective rain - Rainfall minus interception.

efficiency - The ratio of output of a process to the input required to produce it, expressed as a percentage.

erosion - The process of wearing away of soil and parent material by the action of water and wind.

evaporation - The process by which water becomes vapor, including vaporization from free water surfaces, from land surfaces, and from snow, but excluding transpiration; also, the quantity of water which is evaporated.

evapo-transpiration - Evaporation plus transpiration.

excess rain - Effective rainfall in excess of infiltration capacity.

exotic - Not native to the place where found.

fertilizing - The application of manure or a chemical substance to make soil more fertile.

flume - Conduit or chute for conveying water.

frequency curve - A curve showing the relation between (1) magnitude of item and percentage of items of magnitude equal to or greater (or smaller) than the various magnitudes shown; also, a curve showing the relation between (1) magnitude of item and (2) recurrence interval.

frost-free period - The period when there is no likelihood of frost, usually expressed in days.

geomorphology - The study of the relief features of the earth's surface.

growing season - The period of the year when plants are actively growing.

ground water - Subsurface water occupying the saturated zone, from which wells and springs are fed. Also called phreatic water.

gully, gullying - A trench eroded in the earth by running water after rains.

hardpan - A shallow layer of earth material which has become relatively hard and impermeable, usually through deposition of minerals.

harvesting - The act or process of gathering in a crop after it matures.

hydrograph - A graph showing discharge or some function of discharge vs. time.

hydrologic cycle - The never ending water-transfer cycle, the main parts of which are (1) evapo-transpiration, (2) precipitation, and (3) runoff.

hydrologic equation - The water inventory equation (Inflow = Outflow + Change in Storage) which expresses the basic principle that during a given time interval the total inflow to an area must equal the total outflow plus the net change in storage.

hydrology - The study of the characteristics and occurrence of water, and of the hydrologic cycle. Engineering hydrology pays particular attention to the runoff phase of the hydrologic cycle, and emphasizes the hydrologic equation.

import - Water piped or channeled into an area.

index of wetness - The precipitation for a given year expressed as a ratio to the mean annual precipitation.

indigenous - Native to a particular region or environment.

infiltration - Flow of water in a general downward direction from the land surface through the soil and intermediate zones toward the water table; also, the quantity of water which infiltrates.

infiltration capacity - The rate at which infiltration would occur at the land surface at a given time under conditions of unlimited supply.

infiltration capacity curve - A graph showing the time-variation of infiltration capacity. A standard infiltration capacity curve shows the time-variation of the infiltration rate which would occur if the supply were continually in excess of infiltration capacity.

infiltrometer - An instrument for measuring infiltration capacity.

influent - Water flowing into a reservoir or basin.

interception - The catching of precipitation by vegetation so that it never reaches the land surface.

irrigation - Application of water from sources other than rainfall to supply crop water requirements.

isohyetal map - A map showing lines of equal precipitation.

land evaporation - Evaporation from land surfaces, in contrast to evaporation from free water surfaces.

land leveling - The process of creating a plane surface on the land.

land shaping - The process of adjusting the surface of the land to obtain desired characteristics.

land smoothing - Elimination of major humps and depressions of the land surface.

leaching - The removal of salts and alkali from soils by percolating water or by abundant irrigation combined with drainage.

manhole - An opening by which access may be achieved for inspection, maintenance or repair of a buried structure.

mass curve - A graph showing the cumulative volume of discharge or rainfall (ordinate) vs. time.

mean - The sum of the magnitudes of all items of a set, divided by the number of items.

median - The magnitude of item such that half of the total number of items are larger and half are smaller.

moisture deficit - The difference between the amount of water supplied and the amount required as by a crop.

natural control - A stream-gaging control which is natural to the stream channel, in contrast to an artificial control constructed by man.

net rain - The portion of rainfall which reaches a stream channel or the concentration point as direct surface flow.

overflow device - A structure to permit and control the flow of excess water from one place to another.

Parshall flume - A calibrated device for measuring the flow of water in an open channel. It consists essentially of a contracting length, a throat, and an expanding length. Flow through the device is determined by measuring the head of water at a specific distance from a sill over which water passes.

paving - The process of covering the surface with material to make it firm and less permeable.

percolation - The movement or flow of water through the interstices or the pores of a soil or other porous medium.

permanent control - A stream-gaging control which is substantially unchanging, and is not appreciably affected by scour, fill, or backwater.

permeability - The property of a soil or rock material that permits appreciable movement of water through it when it is saturated and the movement is actuated by hydrostatic pressure of the magnitude normally encountered in natural subsurface water.

pest control, pest management - The practices followed in controlling the damage to crops caused by birds, insects, rodents and other browsing and grazing animals. Sometimes includes weed control.

phreatophyte - A plant which customarily feeds on ground water and the associated capillary fringe.

planting - The process of putting or setting seeds or cuttings in the soil for growth.

plowing - The process of turning, breaking up, or working the soil with an implement.

point discharge - Instantaneous rate of discharge, in contrast to the mean rate for an interval of time.

point precipitation - Precipitation at a particular site, in contrast to the mean precipitation over an area.

porosity - The capacity of rock or soil to contain water. The amount of water that rock can contain depends on the open spaces between the grains or cracks that can fill with water. Well-sorted soil is more porous than poorly-sorted soil. Soil is well sorted if the grains are all about the same size (as in the case of gravel or sand); poorly-sorted soil thus has less porosity than well-sorted.

potential evapo-transpiration - The amount of evapotranspiration which would occur in a region if there were no moisture deficit during the growing season.

precipitation - Rain, snow, hail, dew and frost.

probability - The number of times something will probably occur over the range of probable occurrences, expressed as a ratio.

pumping - Lifting water or forcing it through a pipeline or other closed conduit.

pumpback system - A system to collect excess runoff and return it to a higher elevation for reapplication.

quality of water - The physical, chemical, and biological characteristics of water relating to its suitability for a given use.

rain, rainfall - Water falling in drops condensed from vapor in the atmosphere, measured by depth.

rainfall distribution (time, space) - The manner in which the total rainfall is distributed in a region by either time or geography.

rainfall probability - The likelihood of receiving a given rainfall in a certain time.

rainfall-runoff relationship - The relationship of the amount of runoff which occurs as a result of receiving a certain rainfall.

rainfed farming - System of farming which depends entirely on using rainfall (and other forms of precipitation) to supply crop water requirements.

rating curve - In stream gaging, a graph showing the relationship between gage height and rate of discharge.

reach - A specific portion of the length of a stream channel.

recurrence interval - The average number of years during which an event of magnitude equal to or greater (or smaller) than a given value is expected to occur once.

relative humidity - The amount of water vapor in the air, expressed as a fraction of the amount in the air if saturated at the same temperature.

relief - The difference in elevations of a land surface.

reservoir - A water storage facility.

retention - The part of the gross storm rainfall which is intercepted, stored, or delayed, and thus fails to reach the concentration point by either surface or subsurface routes during the time period under consideration.

riprap - Broken stone or boulders placed compactly or irregularly on dams, levees, dikes, or similar embankments for protection of earth surfaces against the erosive action of waves or currents.

river basin - The area drained by a river and its tributaries.

root zone - The subsurface zone from the land surface to the depth penetrated by roots.

runoff - Drainage or flood discharge from rainfall which leaves an area as surface flow or as pipeline flow, having reached a channel or pipeline by either surface or subsurface routes; see also runoff percentage.

runoff area - The area which produces runoff from rain.

runoff event - The occurrence of runoff after rain.

runoff farming - The direct use of runoff for crop production.

runoff percentage - Runoff expressed as a percentage of the precipitation.

salinity, salinization - The content of salts, the process of becoming salty.

sedimentation - The deposition of suspended matter carried by water by gravity. It usually occurs by reducing the velocity of the water below the point at which it can transport the suspended material.

sedimentation basin/tank - A basin or tank in which water containing settleable solids is retained to remove by gravity a part of the suspended matter. Also called settling basin, settling tank.

seepage - The loss of water by infiltration from a canal, reservoir, or other body of water.

shifting control - A stream-gaging control which is affected by scour, fill, or backwater.

slope - Upward or downward slant or inclination of a surface.

soil - A complex system of solid, liquid, and gaseous material with particles of varying size, shape, and chemical composition; the medium for plant growth.

soil amendment - Material added to the soil to change its physical or chemical characteristics.

soil depth - The depth of soil above the parent material.

soil moisture - Water in the root zone.

soil profile (layering) - The various layers of soil of different types in the total soil depth.

soil type or class - The designation of soils based on origin and physical and chemical properties.

soil uniformity - The extent to which the soil is variable in depth or throughout an area.

soil zone - Root zone.

stage - Water-surface elevation or gage height.

storm loss - Infiltration plus depression storage, also includes the interception loss in some cases.

stream gaging - The collection of stream-flow data by direct measurements of discharge and water-surface elevation.

supplemental irrigation - Irrigation applied to supplement water supplied by rainfall.

surface detention - Detention storage.

terrace - A level land area constructed on a hillside or in a waterway to catch runoff and make crop production easier or better.

terrain - The physical features of a parcel of land.

topography - The configuration of a surface including its relief and the position of its natural and man-made features.

total annual rainfall - The amount of rain (precipitation) received in a year at a given location.

transpiration - The vaporization of water given off by plants; also the quantity of water which is thus vaporized.

ultimate infiltration capacity - The relatively low and steady infiltration capacity which exists after a sufficiently long period of infiltration at capacity rate.

water - A transparent, odorless, tasteless liquid, a compound of hydrogen and oxygen, H_2O, freezing at 0°C and boiling at 100°C, which, in more or less impure state, constitutes rain, oceans, lakes, rivers, and other such bodies.

water collection efficiency - The ratio of runoff to precipitation from a surface used to collect water.

water control - The process of controlling the quantity of flow and distribution of water.

water conveyance - The movement of water from one place to another through canals, flumes, pipelines, or natural (controlled) channels.

water harvesting - Collection and utilization of rainfall and runoff.

water management - The process of managing water for the benefit of people and animals.

water rights - The legal powers or privileges recognized as validly existing under the applicable system of law, in, upon, or concerning waters.

watershed - The area contained within a divide above a specified point on a stream. In water supply engineering, it is called a watershed or a catchment area; in river control engineering, it is called a drainage area, a drainage basin, or a catchment area.

water spreading - Controlled distribution of water from a stream channel to the adjacent land for the purpose of recharging ground-water aquifers or for crop production.

water spreading dam - A low dam placed across a stream channel for the purpose of spreading the flow to adjacent land.

water storage efficiency - The ratio of water put into a storage facility to that amount taken out for use.

water table - The upper surface of the zone of saturation, except where that surface is formed by an impermeable body.

weir - A device that has a crest and some side containment of known geometric shape, such as a V, trapezoid, or rectangle, and is used to measure flow of liquids in open channels. Flow is related to upstream height of water above the crest, to position of crest with respect to downstream water surface, and to geometry of the weir opening.

MEMO

To: Students Purchasing Class Notes
From: Student Union Fast Copy

Subject: Awareness of Services

As a currently enrolled University of Arizona student, Fast Copy would like to notify you about some of the other services available to you from this photocopy center.

A partial listing of these services include:

- COPIES
- FAX # - (602) 621-5303
- DESKTOP PUBLISHING
- BINDING
- RESUME SERVICE
- OVERHEAD TRANSPARENCIES
- ENLARGEMENT/REDUCTION
- 5 CENT COIN-OPERATED COPIERS

If you have any questions, please feel free to come to us for assistance.

NOTICE: In compliance with Arizona law, the goods, services or facilities provided by the Student Union Fast Copy Center are offered only to students, faculty and staff of this university, and to those invited guests who are on campus for educational, research or public service activities.