

Proceedings of the Fourth Agriculture Sector Symposium

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Editor

The World Bank
Washington, D.C., U.S.A.

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First printing September 1984

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The fourth Agriculture Sector Symposium was cosponsored by the Agriculture and Rural Development Department and the Staff Training Division, Personnel Management Department, of the World Bank.

Library of Congress Cataloging in Publication Data

Agriculture Sector Symposium (1984 : World Bank)
Proceedings of the Fourth Agriculture Sector Symposium.

"Co-sponsored by Agriculture and Rural Development Department and the Staff Training Division, Personnel Management Department, the World Bank."

Includes index.

1. Agriculture--Economic aspects--Developing countries
--Congresses. I. Davis, Ted J., 1930-. II. World
Bank. Agriculture and Rural Development Dept.
III. World Bank. Staff Training Division. IV. Title.
HD1417.A48 1984 338.1'09172'4 84-19545
ISBN 0-8213-0417-8

WATER HARVESTING, INCLUDING NEW TECHNIQUES OF
MAXIMIZING RAINFALL USE IN SEMIARID AREAS¹

by

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INTRODUCTION

Purpose and Scope:

Water harvesting is an ancient method of water supply that has received renewed interest in recent years. There is a considerable amount of technical literature which describes or presents information concerning the various techniques for maximizing rainfall use. Unfortunately, much of this information is scattered in the many scientific or technical journals and proceedings of various meetings, and are written in a manner which is difficult to interpret for direct field application by farmers and technicians. This paper is a summary of some of the methods and materials used to collect and store precipitation runoff for the growing of crops, and to provide drinking water supplies for man and animals. It is not practical to list or describe every technique, but the more effective concepts and methods are outlined. While the general techniques are potentially feasible for use in any part of the world, the main emphasis of the paper is directed to the arid and semiarid regions.

The installation and operation costs of the described systems are highly dependent upon the local availability of materials, labor, and equipment. In times of high inflation and rapidly changing values, it is difficult to make direct cost comparisons. When appropriate, costs of various systems or components are presented. Case histories of some of the systems are presented to illustrate installation techniques, performance, and potential problems. In addition to direct field studies by the author, much of the information in this paper is derived from the proceedings of two international symposia and a U.S. Department of Agriculture Agricultural Handbook (Frasier, 1975; Dutt et al, 1981; Frasier and Myers, 1983).

Definitions:

Water harvesting is the term used to describe the process of collecting and storing water from an area that has been treated to increase precipitation runoff. A water-harvesting system is the complete facility for collecting and storing the runoff water. It is composed of a catchment or water-collecting area, the water storage facility, and various auxiliary components such as fencing, sediment or trash traps, and evaporation control (Fig. 1).

¹Presented at the World Bank's Fourth Annual Agricultural Sector Symposium, 9-13 January, 1984, Washington, DC.

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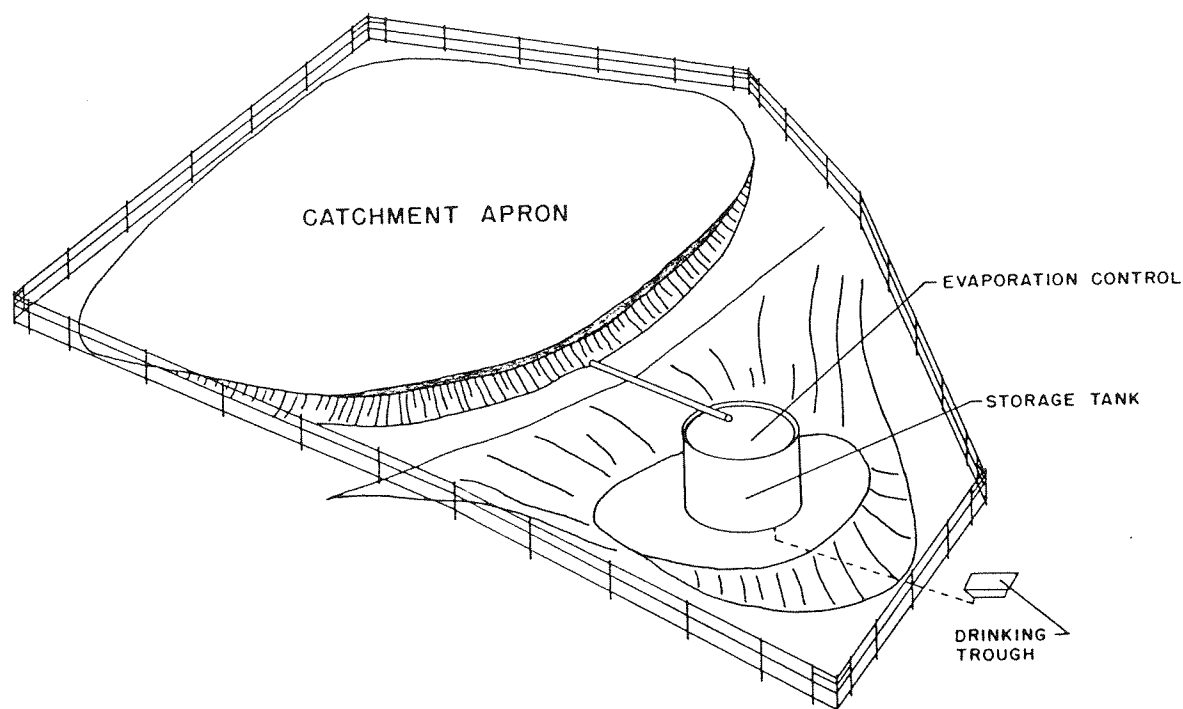


Figure 1. Idealized sketch of a water harvesting facility for supplying drinking water.

The catchment area is the component of a water-harvesting system that collects and concentrates the precipitation. Any area that is reasonably impermeable to water infiltration can be used as a catchment. Large expanses of rock outcroppings can be natural surfaces which are potentially suitable for a catchment. Paved highways and roofs of buildings are examples of surfaces designed for other uses which, by adding troughs or gutters, can be used for water collection. In many water-harvesting systems, the catchment apron is a specific area of land that is cleared of all vegetation, shaped, smoothed, and then chemically treated or covered with an impermeable membrane to stop water infiltration.

The storage tank is the component of a water-harvesting system that stores the collected water until it is needed. Any container that prevents unwanted water loss is a potential method of water storage. For drinking-water supplies, and some crop-growing systems, typical storage tanks are earthen reservoirs, lined pits, and various steel, plastic, concrete, or wooden tanks. Many storage tanks are completely enclosed. Open top storage tanks usually require some means of reducing or preventing water loss by evaporation. Typical evaporation control methods are roofs or covers floating on the water's surface. For some crop growing water-harvesting systems, the water storage facility is the soil profile in the growing area.

Runoff farming is a water-harvesting system specifically designed to furnish water for growing plants (Fig. 2). There are two general types of runoff-farming systems. These are: (1) A system where the collected water is stored in a pit or tank for later application to the crop grow area. These systems usually utilize some form of furrow, sprinkle, or trickle irrigation

system for water application to the crop. (2) A system which utilizes the soil as the water storage container. The plants withdraw the moisture directly from the soil.

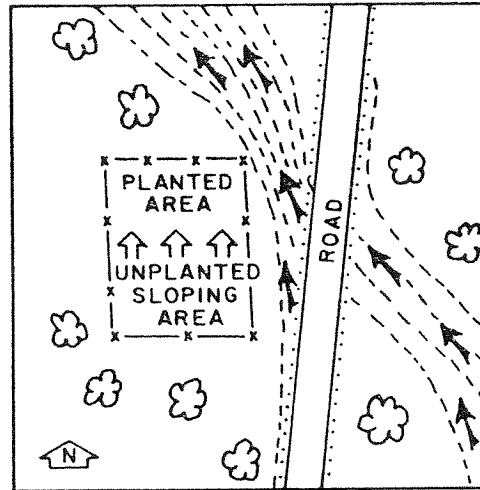


Figure 2. A dry farming agriculture system near Crystal, New Mexico (Billy, 1981)

Water spreading is a form of runoff farming that usually does not have a specific prepared catchment area. Runoff water from upslope or from intermittent flowing channels is diverted into contour ditches or terraces, and allowed to spread as shallow flow across the land (Fig. 3). The ditches or terraces direct and retain the water on the soil surface to allow for longer periods of water infiltration.

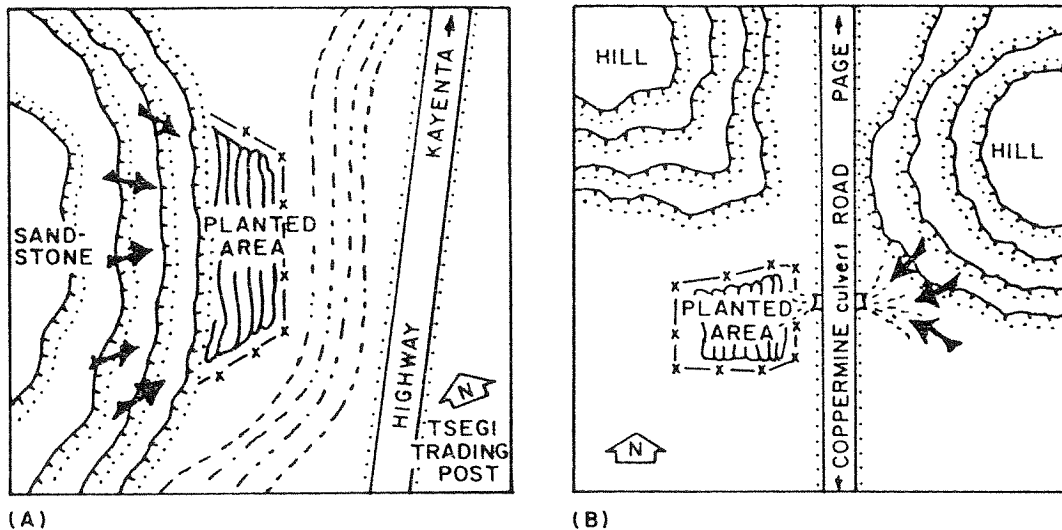


Figure 3. Water-spreading, runoff-farming systems, (a) John Boyd floodwater farming area near Coppermine, Arizona; (b) Tsegi Canyon floodwater farming near Kayenta, Arizona (Billy, 1981).

HISTORY OF WATER HARVESTING

4,000 BC to 2,500 BC:

It is probable that the first water-harvesting system was simply an excavated pit or other water storage container placed at the outfall of a rocky ledge to catch the runoff water during a rainstorm. The next evolutionary step might have been the construction of a rock diversion wall or gutter to provide a larger collection area. There is evidence in Iraq that these simple forms of water harvesting were practiced in the Ur areas as long ago as 4,500 BC. Along the desert roads, from the Arabian Gulf to Mecca, there still exist water-harvesting systems that were constructed to supply water for trade caravans (Hardan, 1975).

2,500 BC to 1,800 AD:

One of the earliest documented runoff farming installations is located in the Negev Desert of Israel. Evanari and his colleagues described and partially reconstructed some of these water-harvesting systems which are thought to have been built about 4,000 years ago (Evanari et al., 1961). In these systems, hillsides were cleared and the soil smoothed to increase runoff. Contour ditches conveyed the collected water to lower-lying fields to irrigate crops. These systems operated in an area that today has an average annual total precipitation of approximately 100 mm. This was the first comprehensive description of an agricultural system dependent upon rainfall collection. There is evidence that similar systems were used 500 years ago by Indians in the Southwestern region of the United States (Woodbury, 1963).

1,800 AD to Present:

A common method of early water harvesting was collecting runoff from the roofs of buildings and storing the water in cisterns or tanks. During the early settlement period of the United States, and other countries, rooftop water was often the only source of domestic water. This technique is still used today in areas of limited surface and groundwater, such as Hawaii and other volcanic tropical islands.

The first catchments, constructed solely as a water supply for animals, were rooflike structures of galvanized sheet metal on a wooden frame. These catchments were effective, but also relatively expensive. In later installations, the sheetmetal was placed directly on the soil surface. Other materials, such as concrete, tar paper, and soil cement, have been used as catchment treatments, with limited degrees of success. Unfortunately, the effective life of many materials did not justify the cost of the materials or the labor for installation.

During the 1950's, many catchments in the western United States were constructed with coverings of artificial rubber (butyl) membranes. These membranes had good resistance to sunlight deterioration and were relatively easy to install. Unfortunately, many of these catchments failed within 5 to 10

years, usually from wind damage, but improper installation and lack of adequate maintenance were also contributing factors. In the 1960's, various government, private, and university research organizations, primarily located in arid and semiarid countries, initiated studies to develop and evaluate new methods and materials for constructing water-harvesting systems. Primary objectives were to lower installation costs and improve system reliability. Many of these studies have subsequently been discontinued.

Runoff farming and water spreading practices are in limited use around the world. Most of the more effective operational systems have evolved over a period of time, primarily by trial and error techniques. In the United States, the majority of the systems are located on Indian lands in the Southwest. These are usually one or two family-sized plots for growing corn, beans, squash, and melons. Larger systems are being used in rural areas of Mexico for growing corn and beans.

WATER-HARVESTING SYSTEM DESIGN

The design of a water-harvesting system is basically the same for all locations, irrespective of the ultimate use of the collected water. There are many separate elements which must be considered such as: precipitation patterns, water requirement patterns, land topography, alternate water sources, availability of materials, equipment, labor, and acceptability of water-harvesting concepts by the water user. Many of these factors are interrelated, and must be simultaneously considered.

Alternate Water Sources:

Water harvesting is not an inexpensive method of water supply. It does have the advantage of being able to supply water in most areas when other methods are not feasible. To insure that time and money are not wasted, various alternative methods of water supply should be considered prior to installation of a water-harvesting system. There have been instances where the local people were aware of other potential water sources such as undeveloped springs or shallow ground-water, but technicians not familiar with the area made the decision to use water-harvesting as the method of water supply without thoroughly investigating the other potential sources. All potential water sources should be evaluated with respect to number, location, dependability, quality, and quantity. Incorporating and utilizing temporary or intermittent water sources into the total water supply system can, in some places, allow installation of smaller water-harvesting systems. The catchment supplied water can be saved for periods when the intermittent sources are dried up. This practice is of major importance during periods of extended drought.

Water Requirements:

The total water quantity and seasonal distribution requirements vary for each installation. The complete water supply system, including temporary water sources, must be able to meet these requirements. Table 1 lists the

total consumptive water use at Mesa, Arizona for a few common crops. Table 2 gives some estimates of daily domestic household use and daily drinking water requirements of various types of animals. This data is used to estimate the total water quantity which the system will have to supply. Part of the total water requirements are losses of water from storage by seepage and evaporation. Unlined excavated earthen tanks often have seepage losses greater than 25 mm/day. Evaporation losses from open water surfaces can exceed 6 mm/day (Cooley, 1970). Failure to include these losses in the water requirement can result in an undersized system and insufficient water during critical periods.

Table 1. Total consumptive water use for selected crops (Erie et al., 1982)

Crop	Period of growth	Total seasonal use mm
Cash or Oil Crops		
Castor beans	Apr - Nov	1130
Cotton	Apr - Nov	1050
Flax	Nov - Jun	795
Safflower	Jan - Jul	1150
Soybeans	Jun - Oct	560
Sugar beets	Oct - Jul	1090
Lawn or Hay Crops		
Alfalfa	Feb - Nov	2030
Bermuda grass	Apr - Oct	1100
Blue panic grass	Apr - Nov	1330
Small Grain Crops		
Barley	Nov - May	635
Sorghum	Jul - Oct	645
Wheat	Nov - May	655
Fruits		
Grapefruit	Jan - Dec	1215
Grapes (early maturing)	Mar - Jun	380
Grapes (late maturing)	Mar - Jul	500
Oranges (navel)	Jan - Dec	990
Vegetables		
Broccoli	Sep - Feb	500
Cabbage (early)	Sep - Jan	435
Cabbage (late)	Sep - Mar	620
Cantaloup (early)	Apr - Jul	520
Cantaloup (late)	Aug - Nov	430
Carrots	Sep - Mar	420
Cauliflower	Sep - Jan	470
Lettuce	Sep - Dec	215
Onions (dry)	Nov - May	590
Onions (green)	Sep - Jan	445
Potatoes	Feb - Jun	620
Corn (sweet)	Mar - Jun	500
Green Manure Crops		
Guar	Jul - Oct	590
Peas (papago)	Jan - May	495
Sesbania	Jul - Sep	330

Table 2. Estimates of daily water requirement for domestic use and drinking water for various animals (Frasier and Myers, 1983).

Use	Daily water requirements
	Liters per day
Domestic	
Per person cooking, drinking, and washing	40
Additional for flush toilets and showers	75-150
Animal drinking	
Beef cattle	
Mature animals	30-45
Cows with calves	40-85
Calves	20-30
Dairy cattle	
Mature animals	40-55
Cows with calves	45-70
Sheep	
Mature animals	4-8
Ewes with lambs	6-10
Horses	
	40-45
Wildlife	
Mule deer	4-8
Antelope	1-2
Elk	20-30
Swine	
	15
Chickens (per 100 head)	15
Turkeys (per 100 head)	25

Of equal importance to the total water requirement is the timing of the water needs. For runoff farming applications, the crop-growing season is the time of water need. Figure 4 is an example of the seasonal distribution of water requirements for a crop of barley. Total water requirement is 635 mm, with most of the water required in March and April, when the grain is in a stage of maximum growth and seed development. This water requirement pattern must be satisfied by the design of the water-harvesting system. The daily water requirements of some other common crops is presented in Erie et al., 1982. This information was developed under extensive irrigation practices, and will probably be higher than needed for many runoff farming applications. For many domestic and livestock drinking supplies, the water needs may be relatively constant throughout the year, but there are various range management practices, such as rotational grazing patterns, which require a non-uniform distribution of water during the year.

Precipitation:

The quantity of precipitation which might occur during a given time period is one of the most difficult parameters to accurately depict. Monthly averages, obtained from long-term precipitation records, are the most common data base. Short-term random fluctuations from the mean can significantly affect the performance of a water-harvesting system. To minimize the effect of precipitation variations, it is desirable to use a minimum of 10 years of

record. If there are extreme variations in precipitation quantities, data from the two wettest years should be eliminated. If sufficient long-term data are available, selecting rainfall amounts based on probability analysis techniques can assist in designing the most optimum system.

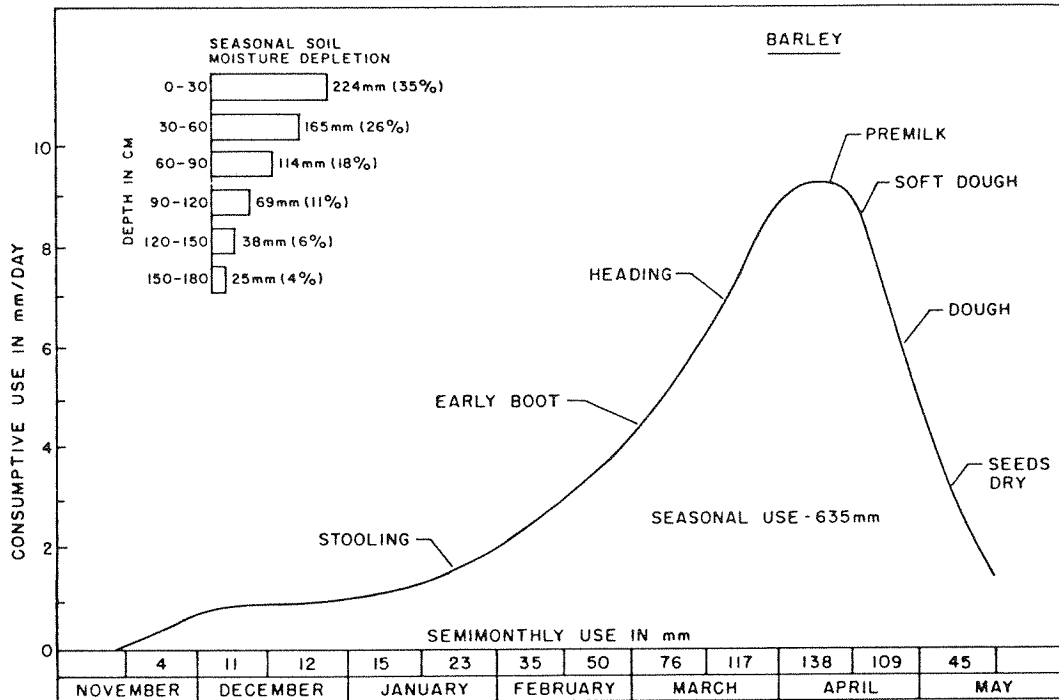


Figure 4. Mean Consumptive use for barley at Mesa, Arizona for years 1952-53, 1969-70 (Erie et al., 1982).

In most areas, there will be periods when the precipitation quantity will be significantly less than was used for the system design, and less water will be collected than is required. To compensate for these periods, the size of either the catchment area or the storage volume, or both, can be increased. It is usually not economically feasible to design a water-harvesting system to meet the least expected precipitation. The user must decide the amount of risk that can be accepted should there be insufficient precipitation during some periods.

The final size of the catchment area and storage tank should be determined by computing an incremental (monthly or weekly) water budget of collected water versus water requirement. This is to insure that there are no critical periods where there will be insufficient water. Monthly intervals are commonly used increments. Smaller systems can frequently be used when the periods of maximum precipitation coincide with the periods of maximum use. Larger systems, especially the water storages, are usually necessary when the periods of greatest precipitation occur after the periods of greatest water needs when it may be necessary to store the water for periods of 6 to 9

months. In many installations, there will be several combinations of catchment and storage sizes which will provide the required quantities of water. The lowest total cost system will frequently be one with a reduced storage.

Availability of Materials and Labor:

There is no universally best material for catchment and storage. The cost of alternative water sources, and the importance of the water supply, determine the costs which can be justified in a system. Ordinarily, the lowest cost locally available materials are used. Usually, water-harvesting systems for supplying drinking water are constructed from materials which are more costly than can be economically justified for runoff-farming applications. One must balance the cost of materials to the cost of labor. Some materials and installation techniques are labor intensive, but have a relatively low capital costs. Other materials may be higher in initial cost, but require a minimum of labor for proper construction.

Acceptance and Need as Viewed by User:

In the design and construction of any water-harvesting system, the user of the system must be involved as much as possible. The success and performance of the system will depend upon the user for proper operation and maintenance. Some materials and/or system designs require more maintenance than others. If the user cannot provide the maintenance required, the system will fail. Also, in some areas, new ideas, such as water harvesting, may not be acceptable because of various social or economic factors. The user must believe that the system is the best for his purpose or situation. Otherwise, there will be problems of proper operation and maintenance of the system. In areas where the concepts of water harvesting and runoff farming are not fully accepted, the first system installed must be constructed from materials which have minimum maintenance requirements and maximum effectiveness. The extra cost encountered in building a good system may be necessary to insure acceptance of the concept by the user. Once the concepts are accepted, it is often possible to utilize lower cost materials and techniques on subsequent units even though these lower cost systems may have a greater chance of failure or require additional effort from the user. If the user has been shown the ideas are valid, he will usually expend the extra effort to properly operate and maintain a system.

CATCHMENT AREA TREATMENTS

There are many ways that an area can be modified to increase the quantity of precipitation runoff. These can be separated into three general categories: (1) topography modifications, (2) soil modifications, and (3) impermeable coverings or membranes. Many catchment treatments are composed of a combination of these methods. Any impermeable or waterproofed area can be used as a catchment surface. The addition of gutters and downspouts to the roofs of buildings is one of the simplest methods of obtaining water for domestic use. Table 3 presents a list of some of the more common catchment treatments

which are in present usage along with design estimates of runoff efficiency, expected life, and initial cost per unit area of materials. Each specific site will have a treatment that is best suited. A different treatment may be the best for a different site only a short distance away.

Table 3. Potential water-harvesting catchment treatments (Frasier, 1981).

Treatment	Runoff efficiency	Estimated life	Materials initial cost ¹
<u>Topography Modifications:</u>			
	(%)	(years)	(\$/m ²)
Land smoothing and clearing	20 - 35	5 - 10	0.05 - 0.20
<u>Soil Modifications:</u>			
Sodium salts	50 - 80	5 - 10	0.20 - 0.50
Water repellents, paraffin wax	60 - 95	5 - 8	0.50 - 1.00
Bitumen, asphalts	50 - 85	2 - 5	1.00 - 2.00
<u>Impermeable Coverings:</u>			
Gravel covered sheetings	75 - 95	10 - 20	1.00 - 1.75
Asphalt-fabric membranes	85 - 95	10 - 20	1.75 - 2.50
Concrete, sheetmetal, artificial rubber	60 - 95	10 - 20	5.00 - 20.00

¹Adjusted to 1983 material costs.

Topography Modifications:

The earliest catchment treatments are believed to have involved some form of topography modifications, and were simply prepared by clearing an area of brush and rocks with small collection or diversion ditches to direct the runoff water to the storage tank. An example of this technique is the placement of water collection channels at the lower edge of rock outcroppings. Small masonry dams on the lips or outfall of a rock area may be constructed with a minimum of materials or skilled labor, and will provide relatively large quantities of water at low costs.

Some of the most extensive uses of catchments utilizing topography modification techniques are the "roaded" catchments in Western Australia (Fig. 5). A roaded catchment consists of

". . . parallel ridges ("roads") of steep, bare and compacted earth, surveyed at a gradient that allows runoff to occur without causing erosion of the intervening channels." (Laing, 1981)

In 1980, it was estimated that there were more than 3,500 roaded catchment systems in Western Australia, comprising a total area in excess of 5,000 hectares. Many of these catchments have a top dressing, or layer of compacted clay, to increase the runoff efficiency (Frith, 1975).

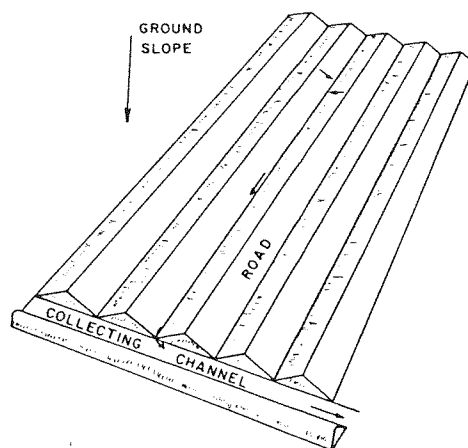


Figure 5. Australian roaded catchment (Hollick, 1975).

Catchments utilizing topography modification techniques, such as the roaded catchments, are usually characterized with low initial costs, but may have relatively low runoff efficiencies. These treatments are effective if properly matched to suitable soil types and topographic features. Improper design of slope angles and overland flow distances can result in serious damage to the catchment surface by water erosion (Hollick, 1975).

Soil Modifications:

Soil modifications are chemical treatments applied to the soil surface by spraying or mixing to reduce, or stop, water infiltration. These treatments can potentially provide large quantities of low cost water. Many types of chemicals have been evaluated, but unfortunately, most of the materials were not successful because of specific soil characteristic requirements or inadequate life. Bitumen or asphaltic materials have been one of the more widespread evaluated materials. These materials are limited to application on fine, sandy soils (Laing, 1981; Myers et al., 1967), and have an effective life of 2 to 5 years.

One of the potentially lowest cost soil modification techniques is the sodium dispersed clay or salt treatment. This treatment consists of mixing a water soluble sodium based salt (NaCl) at a rate of about 11 metric tons per hectare into the top 2 cm of soil. After mixing the salt with the soil, the area is wetted and compacted to a firm, smooth surface. This treatment apparently requires a soil with 20 percent, or more, of a kaolinite or illite type clay. The sodium salt disperses the clay, which plugs the soil pores and reduces the rate of water permeability (Dutt, 1981). Soil erosion may be a potential problem.

A second type of potentially low cost soil modification are the water repellent treatments. A chemical is applied to the catchment surface, which

causes the soil to become hydrophobic or water repellent. These treatments usually do not change the porosity of the soil. Instead, the waterproofing is caused by changing the surface tension characteristics between the water and soil particles. Many chemicals can create a water repellent surface, but only a few compounds have been shown to be effective for water-harvesting applications (Myers and Frasier, 1969).

One of the simplest water repellent chemicals to apply is a water-based sodium silanolate. This material, when applied as a dilute solution, reacts with the soil particles to form a water repellent layer 1 - 2 cm deep, with an effective life of 3 - 5 years. The treatment does not provide any soil stabilization, and erosion by water and wind can be a problem. Also, it is not suited for soils containing over 15 percent clay. It does have high potential for increasing runoff from rock outcroppings where soil erosion is not a potential problem.

Another water repellent treatment is the paraffin wax. Molten refined paraffin wax is sprayed on the prepared soil surface. Initially, the wax is a thin layer on the surface. As the sun heats the surface, the wax remelts and moves deeper into the soil, coating each individual soil particle with a thin coat of wax, rendering the soil water repellent (Fink et al., 1973). This treatment is best suited for soils containing less than 20 percent clay and catchment sites where the soil temperatures will exceed the melting point of the wax during some part of the year (Frasier, 1980). The paraffin wax does not provide any significant soil stabilization, and the treatment is susceptible to damage by water and wind erosion.

Impermeable Coverings or Membranes:

Most types of plastic and other thin sheetings have been investigated as potential soil coverings for water-harvesting catchments. Unfortunately, most of these thin film coverings are susceptible to mechanical damage and sunlight deterioration. Partial success has been achieved with some of these materials by bonding them to the soil with asphaltic compounds (Frasier and Myers, 1972).

One of the simpler techniques for utilizing low-cost sheets of plastic or roofing tar paper is to place a shallow layer of clean gravel on the sheeting after it has been positioned on the catchment surface. The sheeting is the waterproof membrane, and the gravel protects the sheeting from mechanical and photochemical damage. This treatment does require a periodic maintenance program to insure the sheeting remains covered with the gravel. Runoff is essentially 100 percent of all precipitation in excess of 2 mm. Windblown dust trapped in the gravel layer, providing a seedbed for plants, has been a minor problem. This treatment is relatively inexpensive if clean gravel is readily available (Cluff, 1975).

One effective treatment being used to supply drinking water for wildlife and livestock in the United States is a membrane of asphalt-saturated fabric. A random weave fiberglass matting or a synthetic polyester filter fabric matting is saturated with an asphalt emulsion. The matting is unrolled on the

prepared catchment surface and saturated with the asphalt emulsion. Three to 10 days later, a final asphalt sealcoat is brushed on the membrane. These membranes are relatively resistant to damage by wind, animals, and to weathering processes (Myers and Frasier, 1974).

Many conventional construction materials, such as concrete, sheetmetal, and artificial rubber sheetings, can be used on water-harvesting catchments. These materials are relatively expensive, but when properly installed and maintained, have long lives, and may be the best treatment for some locations. Large expanses of concrete will crack. All cracks and expansion joints must be periodically filled with some type of sealer. Roofs of sheetmetal have long been used to collect rainwater. Costs can be reduced by placing the sheetmetal on the ground. In the 1950's, many catchments were covered with sheets of artificial rubber. Improper placement, plus susceptibility to damage by wind and animals, destroyed most of these units.

WATER STORAGE TECHNIQUES

Water storage techniques can be separated into two general groups: (1) the soil profile or monolith, and (2) tanks or ponds. The type of storage selected will depend upon many factors, such as the ultimate use of the water, availability of construction materials, availability and skill level of labor, and site topography.

Soil Monolith Storages:

In many runoff farming applications, the soil profile within the crop growing area is the water storage container. The primary factors that must be considered in designing soil monolith storages are, (1) the depth of the soil profile, (2) water holding capacity of the soil, and (3) the water infiltration rate of the soil surface. The soil profile should be approximately the same depth as the roots of the plants. Very shallow soil profiles will not have sufficient water storage capacity. Soil profiles significantly deeper than the depth that the roots can withdraw the water will effectively lose the water by deep percolation. Sandy or coarse-textured soils have a high permeability rate which allows for rapid infiltration of the water into the soil, but also a low water-holding capacity which limits the total quantity of water which can be held in the root zone. Conversely, fine-textured soils have higher water holding capacities, but with lower infiltration rates, which may cause problems of getting the water into the soil. Very fine soils (clays) may be unuseable because of very slow infiltration rates of water through the soil surface.

With monolithic water storages, it must be remembered that, in addition to the runoff water from the catchment area, there is also precipitation falling directly on the area which must be infiltrated. Except for very low intensity storms, the rate of runoff will exceed the infiltration rate of the soil, and provisions must be made to temporarily pond the water for a sufficient time period to allow the water to infiltrate. Other factors to consider in selecting soil monolith storages are the total quantity of water which must be

stored to meet the needs of the plants (consumptive use) and the probability of soil water replenishment during the growing season.

Tank or Pond Storages:

Any container capable of holding water is a potential water storage facility. External water storages are a necessary component for drinking water supply systems, and may also be a part of a runoff-farming system where the water is applied to the cropped area by some form of irrigation system. In many water-harvesting systems, the storage facility is the most expensive single item, and may represent up to 50 percent of the total cost.

There is an almost infinite number of types, shapes, and sizes of wooden, metal, and reinforced plastic storages. Costs and availability are primary factors for determining the potential suitability of these storages. One common type of storage is a tank constructed with steel walls, with a concrete bottom or other type of impermeable liner or bottom. Another storage, constructed from concrete and plaster, is relatively inexpensive but does require a significant amount of hand labor.

Unlined earthen pits, or ponds, are usually not satisfactory methods of water storage for water-harvesting systems unless seepage losses can be controlled. In some installations, the seepage can be controlled by liners of plastic or artificial rubber, or the soil sealed with chemicals. Exposed liners are susceptible to damage from wind, sun, animals, and plants. Chemical soil sealants have limited applications, and should only be used as recommended, and if guaranteed by the manufacturer.

Controlling water losses by evaporation is one of the most economical methods of maintaining adequate water supplies, and should be an integral part of any water-storage facility. Roofs over the storages are a common technique, although they are relatively expensive. Floating covers of low-density synthetic foam rubber are effective means for controlling evaporation from vertical walled, open topped storages. Evaporation control on sloping side pits or ponds is difficult to implement, because the water surface area varies as the depth of water changes.

RUNOFF FARMING SYSTEMS

There are two basic types of runoff farming systems. These are a direct water application system where the runoff water is stored in the soil profile of the crop-growing area, and the supplemental water system where the water is stored offsite and applied to the crop as needed with some form of irrigation. In practice, some runoff-farming installations are a combination of the two types.

Direct Water Systems:

In a direct water system, the collected runoff water flows directly onto the crop area during the precipitation event. Dikes or ridges around the crop

area retain the water and allow it to infiltrate into the soil. The runoff water for these systems may be from channels using water-spreading techniques or, more often, obtained from upslope prepared catchment areas.

Systems utilizing water-spreading techniques where the water is diverted from channels or upslope areas may encompass relatively large areas. They have been used for growing grain-type crops and forage grasses. This system has been used by the Papago Indian Tribe, in southern Arizona, for growing gardens. Some of these systems may have extensive ditching systems within the crop area to permit better control of the water. These types of systems in use today have evolved, over periods of many years, by trial and error. New systems, utilizing these techniques, require extensive hydrologic runoff and water infiltration analysis to minimize the possibility of catastrophic failure.

Other direct water runoff farming systems are composed of small prepared catchments directly upslope of the growing area. The runoff water flows only a short distance to the crop. These systems are relatively effective for use in growing shrubs or trees. Runoff to runoff area ratios typically vary from 1:1 to 20:1, depending upon the expected quantity of water which can be collected and infiltrated into the soil profile. Typical catchments range from irregular shaped areas with minimal site preparation and soil treatment to graded, compacted areas which are sealed to maximize the runoff efficiency.

Supplemental Water Systems:

A supplemental water system is one where the runoff is collected and stored offsite of the growing area. The collected water is applied later, as needed, to the crop with some form of irrigation system. These systems have the advantage of being able to supply the water to the crop when it is needed. There is the disadvantage of the extra costs and problems of providing the required water storage and irrigation facilities. If the catchment and storage facilities are located above or upslope of the crop area, simple furrow irrigation systems are effective means of applying the stored water to the crop. A furrow irrigation system is a relatively low cost system to install, but does have the disadvantage of potential water loss from the irrigation ditches.

Within the past decade, installations have been installed which utilize drip or trickle irrigation systems for applying the water. If the catchment and storage facilities are upslope, the required water pressures can be obtained by gravity, alone. Otherwise, the water pressure is obtained by pumps. Trickle and drip irrigation systems have a high water application efficiency, but are expensive to install.

Combination Systems:

These systems, which, as the name implies, are a combination of the direct water application and the supplemental water application techniques. In a combination system, the runoff water flows first to the crop area, where part of it is infiltrated into the soil profile. The excess water flows into a

storage tank or pond for later use. A typical system is composed of land graded into large ridges and furrows (roaded catchments). Crops, such as grapes or fruit trees, are planted in the bottom of the furrows, which have a gradient leading to the storage pond. A trickle irrigation pump back system is used to water the plants as needed.

CASE HISTORIES

Village Water:

Techo Cuenca - Mexico: The Techo Cuenca water harvesting system provides part of the domestic water supply for 30 families (approximately 180 people) for the village of Lagunita y Ranchos Nuevos, in the state of Nuevo Leon, in north-central Mexico. This system, constructed in 1975, consists of an inverted galvanized metal roof (269 m²) supported on a steel framework above an 80,000 liter steel tank, at a cost of 143,000 pesos. Labor for constructing the unit represented 36 percent of the total cost, and was furnished by the village. The system provides drinking water to the entire village for approximately 4 1/2 months per year, based on an allotment of 20 liters per day per family at about one third the cost that is incurred in hauling water (1981 costs; Carmona and Velasco, 1981).

Pan Tak - Papago Indian Reservation: This system is referred to as a village water system, but in reality, it is a multi-family water supply. The Pan Tak Village consists of 3 families (approximately 15 people) located approximately 100 kilometers west of Tucson, Arizona. Annual rainfall is approximately 250 mm, with 60 percent of the total occurring during the July to September "monsoon" season. The village water supply was a shallow well, a 39,000 liter steel, closed top storage tank, and a gravity distribution system to the houses. The well, when pumped slowly, provided an adequate supply for the existing domestic use. The domestic water supply was thought to be a primary deterrent for any increase in the size of the village.

In 1966, a large petroleum company became interested in water harvesting, and constructed a water-harvesting system adjacent to the Pan Tak Village. This system consisted of a 1-hectare catchment, treated with a sprayed asphalt coating, and a 300,000 liter steel rim, concrete bottom tank (uncovered). The design called for allowing the water to seep from the tank to the groundwater, where it would be recovered as needed by the well. The catchment area was reasonably effective in producing runoff for a few years. There are no data or reports as to the success of recharging the groundwater and recovering this water by the well. There was no scheduled maintenance program, and the system was abandoned.

In 1981, a grant was obtained by the Papago Indian Tribe to rejuvenate the system to increase the quantity of water at the village. The lower half of the catchment area was cleared of vegetation, smoothed, and a membrane treatment of gravel-covered polyethylene installed. The large storage tank was cleaned and fitted with a pump, chlorinator, filter unit, and connected to the domestic supply tank. Two years later, this system was not being used, because the local families were not asked for their input and do not want the

village enlarged.

Shungopovi - Hopi Indian Reservation: The village of Shungopovi is located upon Second Mesa, on the Hopi Indian Reservation in northeastern Arizona. The village, built on top of a sandstone rock mesa, had no source of water. From the time of first establishment, the villagers had carried water up from the valley, initially on foot and, later on, on the backs of burros. In the early 1930's, a small water-harvesting system was installed to partially relieve the water shortage of the village. An area of approximately 1/3 hectare was set aside, cleared, and the loose soil removed to expose the sandstone bedrock. Below the area, a deep cistern was hewed into the rock, and a concrete roof constructed. This system was a functional part of the village water supply for about 30 years, at which time, a community well, pump on the valley floor, and water distribution system was installed. In 1974, Chiarella and Beck reported that:

"While the (water harvesting) system was far from meeting the lowest sanitation requirements, it played an important part in supplementing the village water supply."

Livestock Water:

Hualapai Indian Reservation: The Hualapai Indian Reservation covers an area of over 3600 km² in northwestern Arizona. Much of the land is at an elevation above 1500 meters, and is a grassland used for livestock grazing. Large portions of the land are undergrazed because of inadequate animal drinking water supplies. There are very few springs, and earthen stockponds are of marginal benefit because of high seepage and evaporation losses, combined with low runoff into the ponds. There have been a few wells developed, but groundwater supplies are limited and difficult to locate. An extensive pipeline system from the wells has been constructed.

Between 1959 and 1960, the U.S. Department of Interior, Bureau of Indian Affairs, embarked upon a program to use water-harvesting techniques to provide animal drinking water for the area. During this period, a total of 12 units were constructed. The catchment areas varied from 500 to 930 m² on slopes of 6 to over 10 percent. The catchment treatments were an impermeable covering of sheets (1 by 4 meters) of 5 or 10 mm thick asphalt saturated paper. The sheets were butted together and lapped with 20 cm wide gusset strips bonded in place with hot asphalt cement. Each catchment drained into a 150,000 liter open top steel tank. The total cost of installing the systems varied from \$4,200 to \$8,500 at the time of installation, including labor.

All of these catchments had problems. Heat and cold caused an expansion and contraction of the sheets, which pulled the gusset strips loose. Unequal hardening of the asphalt caused curling of the sheets at the edges. Sheeting on several of the catchments installed on the steeper slopes moved downslope, and destroyed the integrity of the covering. Whenever the covering cracked, plant growth became established, which further reduced the runoff efficiency. Within 6 years, 11 of the 12 catchments were inoperable because of the lack of maintenance (Chiarella and Beck, 1975).

One fundamental cause for the failure of these systems was the absence of a planned maintenance program. The Bureau of Indian Affairs was not permitted to allot funds for a maintenance program. The Indian Cattle Grazing Associations, who were the direct users of the area, were not convinced that water harvesting was the best system of water supply for the area, and did not care if the systems worked or failed.

Arizona Strip - Bureau of Land Management: The Arizona Strip is the land across the Colorado River from the Hualapai Indian Reservation and south of the Arizona-Utah state line. The land is under the jurisdiction of the U.S. Department of Interior, Bureau of Land Management, and is leased to cattlemen for grazing by livestock. Perennial streams and springs are rare, and groundwater is inaccessible due to depth and isolation of perched aquifers. Earthen reservoirs are often used, but are rarely dependable because of high seepage, evaporation losses, and low runoff.

Two water-harvesting systems were installed in September, 1974 to evaluate the potential of this technique for supplying the necessary animal drinking water. The catchment areas (0.3 and 0.4 hectares) were treated with a refined paraffin wax sprayed on the prepared soil surface. The collected water was stored in a 300,000 liter steel rim, concrete bottom tank with a foam rubber floating cover for controlling evaporation. Total cost (1974) was \$8,925 and \$9,150, including labor and miscellaneous items such as fencing and drinking troughs. The systems are maintained by the Bureau of Land Management.

During a drought in 1976-1977, these systems provided the only water supplies available. All other water sources went dry. Without this water, the permittees would have had to move their livestock. Ranchers have remarked that these systems were as good as, or better than, a spring (Cooley et al., 1978). Since that time, the Bureau of Land Management has installed over 60 more units of various types and treatments, and several local ranchers are installing units on their own. There have been some failures of the later units, but this has not deterred the ranchers from accepting this method of water supply. This attitude has been developed because it was demonstrated that, with proper installation and maintenance, water harvesting can be an effective method of water supply.

Runoff Farming:

Page Ranch - University of Arizona: The Page Ranch runoff farming facility is located on the University of Arizona Page-Trowbridge Experimental Range north of Tucson, Arizona. The site, at an elevation of 1,200 meters in a 300 to 400 mm rainfall zone, is used as an experimental and demonstration facility, and has several types of runoff-farming systems.

The largest portion of the area is a combination system for growing grapes. The land was shaped into large ridges and furrows. The sides of the ridges were treated with sodium chloride (NaCl) salt mixed into the top 2.5 cm of soil. Grapes are planted in the bottom of the furrows. Excess water from the furrows drains into an excavated pond which was sealed with sodium salts (Fig. 6). The water collected in the pond is pumped back onto the grapes with

a trickle irrigation system (Dutt and McCreary, 1975). This system and a similar system on deciduous fruit trees have been reasonably satisfactory (Mielke and Dutt, 1981). There is a potential problem in this type of system, with eroded clay and silt being deposited around the plants. If this occurs, the deposited soil must be removed to maintain adequate infiltration of the water into the soil in the planted area.

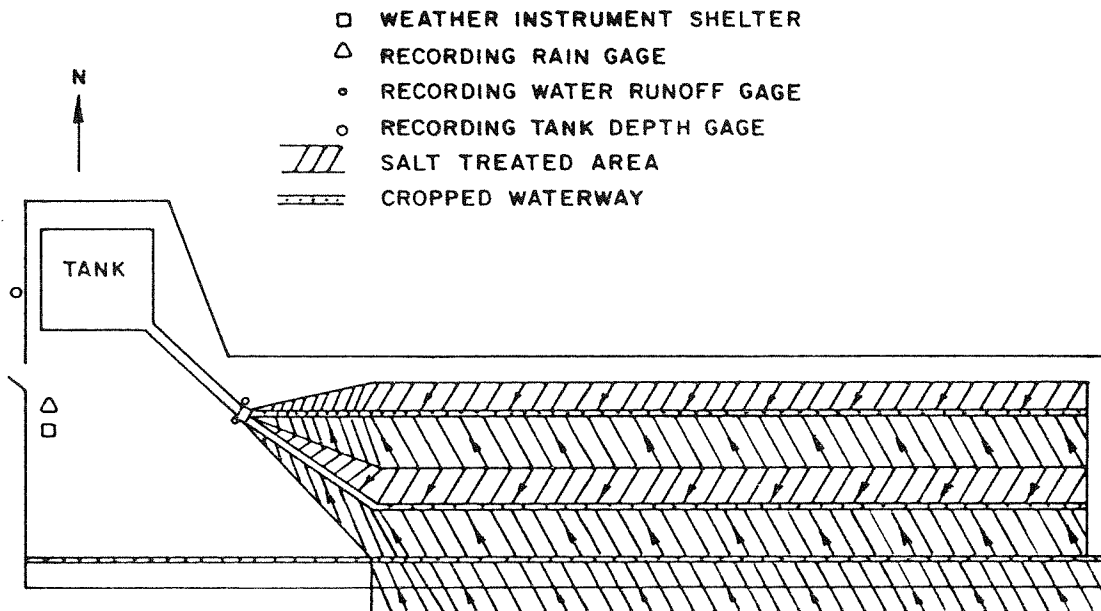


Figure 6. Page-Trowbridge experimental range salt-treated water harvesting, grape and fruit tree plots (Dutt and McCreary, 1975).

Another system used for evaluation of the microcatchment concept for growing various grain crops consisted of contour strips (2.4 m wide), with upslope catchment area (16.3 m wide), formed using moldboard plows and laser controlled scrapers. The runoff areas were compacted with steel rollers to increase the rate of surface runoff. Problems were encountered with birds and rodents damaging the crops, which prevented obtaining a definitive analysis of the system (Flug, 1981).

Mexico: One of the many runoff-farming systems being evaluated in Mexico is located in the state of Nuevo Leon. This system is composed of a set of 248 direct runoff units of 70 m² each for growing pistachio nuts. Each tree has a separate contributing runoff area (Fig. 7). One major objective is to evaluate different treatments on the runoff areas. Treatments under evaluation were: (1) compacted soil, (2) soda ash (Na₂CO₃), (3) road oil, (4) gravel-covered polyethylene, (5) gravel-covered asphalt, and (6) control (smoothed soil). Soil moisture was monitored under each tree at depths of 15, 35, and 55 cm. Also included were various soil coverings immediately around the tree to limit water loss by evaporatin (Velasco and Carmona, 1980).

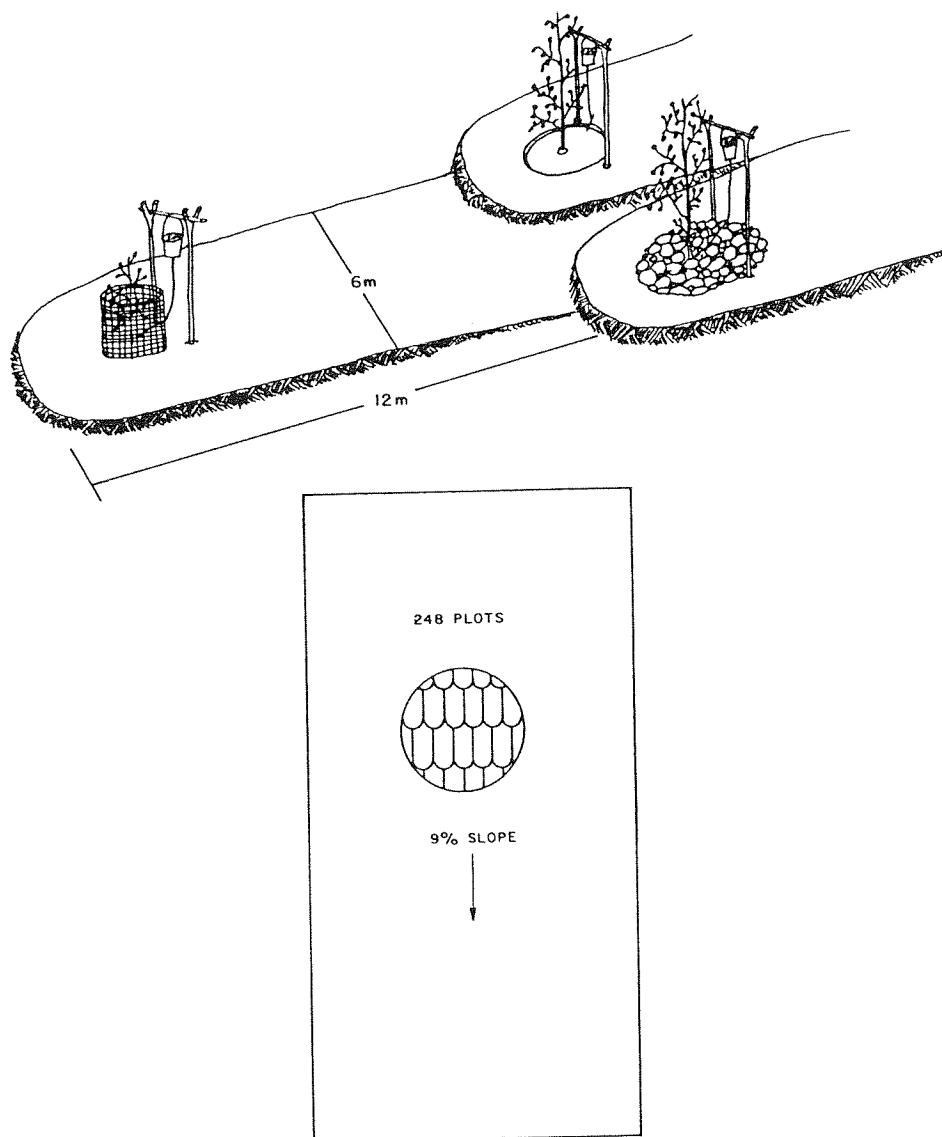


Figure 7. Experimental runoff-farming system for growing pistachio nuts (Velasco and Carmona, 1980).

Because of the slow growth rates of the trees, this is a relatively long-term study. One preliminary observation was that, on some of the salt-treated units, the treated soil eroded from the catchment surface and was deposited around the tree. This treated soil significantly reduced the rate of water infiltration into the soil profile. Some of the collected water was lost by direct evaporation before it could infiltrate into the soil.

U.S. Water Conservation Laboratory: The U.S. Water Conservation Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Phoenix, Arizona has several water-harvesting, runoff-farming research sites. One of the sites, in south central Arizona, was used to determine if the marginal

plant growth and seed yields of native stands of jojoba (Simmondsia chinensis) could be improved with additional water using water-harvesting techniques. For this study, small (20 m²) direct runoff systems were constructed around individual bushes in native stands. Three runoff area treatments, (1) control (undisturbed), (2) compacted and later treated with clay and sodium salts (Na Cl) and (3) paraffin wax water repellent were evaluated. Water use of each plant was determined by neutron soil moisture measurements. Plants receiving the harvested water grew faster and were larger than plants in the untreated neighboring areas. Severe frost conditions were encountered at three separate times during the 7-year study (1974-1980). Because of the frost, it was concluded that commercial farming of jojoba, under the climatic conditions at the test site, would not be practical. This did not mean that the water harvesting approach was wrong, only that, at the particular test site chosen, it was not economically feasible (Fink and Ehrler, 1981).

One of the other test sites is located in north central Arizona. This site is used to determine the feasibility of runoff-farming techniques for growing conifer trees. Level contour benches were constructed with various runoff-runon ratios and catchment area treatments. Two species of tree seedlings were transplanted and watered bi-weekly during the first summer (March to August). Following the first year, the trees received only the water provided by the water-harvesting system. With a few minor exceptions, all trees continued showing satisfactory growth (Fink and Ehrler, 1983).

Black Mesa - University of Arizona: The Black Mesa water-harvesting facility is a combination system located in northeastern Arizona on displaced overburden from a strip coal mine. This is one of the largest systems in the United States. It consists of (1) three water storage ponds with a total capacity of slightly over 3-million liters, (2) two levelled agricultural terraces of 1 hectare each, (3) "road" catchment for an orchard of 0.5 hectares, (4) a fiberglass-asphalt-gravel catchment of 3.2 hectares, and a 2.9 hectare salt-treated catchment. A pump system is used to transfer the collected water between ponds and to lift the water to irrigate the crop areas. Initially, flood irrigation was used, but later, a sprinkler system was installed.

Annual crops grown and evaluated were beets, onions, turnips, potatoes, chard, lettuce, cabbage, tomatoes, squash, beans, pumpkins, melons, mangoes, and corn. All crops, except tomatoes, did well, with some producing at levels above the national average. The value of the corn produced was the lowest of all crops. This was not unexpected, but corn is a traditional food in the area, and was planted for social reasons. Fruit trees had never been grown in the area before. All trees were growing well after 3 years, but it was too soon to determine the potential production of the varieties planted. The water-harvesting project yielded about \$1,700 net revenues per cultivated hectare (1981). Agricultural yields are expected to increase when the orchards reach maturity (Thames and Cluff, 1982).

Southwest Rangeland Watershed Research Center: Limited studies have been conducted, near Tombstone, Arizona by the Southwest Rangeland Watershed Research Center, Agricultural Research Service, U.S. Department of Agriculture, on the effects of additional water provided by a direct application runoff farming system on the forage production of blue panicgrass (Panicum

antidotale Retz). Runoff to crop growing area ratios of 0:1, 1:1, 2:1 and 3:1 were evaluated. Runoff area treatments were (1) bare soil, (2) seeded with grass, and (3) waterproofed with paraffin wax. During a 3-year study, forage yields, using waxed runoff areas of 2:1, were 16 times the control. Adjusting yields to account for the land removed from production with the catchment area shows an average yield 5 times greater from the treated runoff area as compared to an uninterrupted planting of grass (Schreiber and Frasier, 1978). The increased forage production obtained from the waterproofed runoff area is probably not economically feasible for most areas if forage is the only product.

SOCIAL - ECONOMIC CONSIDERATIONS

Water-harvesting/ runoff-farming techniques are technically sound methods of water supply for most parts of the world. What is not often realized is that it is also a relatively expensive method of water supply. During the past few decades, there have been many water-harvesting/runoff-farming systems constructed and evaluated at many different places in the world. Some of the systems have been outstanding successes, while others were complete failures. Some of the systems failed, despite extensive effort, because of material and/or design deficiencies. Many other systems failed, despite proper materials and design, because of social and economic factors that were not adequately integrated into the systems. These systems failed because of personnel changes, the water was not needed, and because of communication failures. Word-of-mouth publicity of one failure will often be more widespread than all of the publicity from 10 successful units.

A successful system must be:

- (1) technically sound, properly designed, and maintained,
- (2) socially acceptable to the water user and his method of operation,
- (3) economically feasible in both initial cost and maintenance at the user level.

There will be a higher probability of system failure when funds are available for construction at no obligation to the user, unless there is a clear understanding of by whom, when, and how the necessary maintenance will be performed. In many places, sociologists and anthropologists are recognized as being a necessary part of any major development program.

STATE-OF-THE-ART

There is no universally "best" system of water harvesting or runoff farming. There will be some type of system which will be the "best" for a given location. Each site has unique characteristics that will influence the design of the most optimum system. All factors, technical, social, and economic, must be considered.

Drinking Water Supplies:

Any impervious area or surface can be used for a catchment surface. The major cost item for a drinking water supply system is the cost of the water storage. Also, a failure of the water storage will negate the expense of the entire system. In most systems, it is not effective to store the collected water in an unlined earthen pond because of high seepage and evaporation losses. Often, the most cost effective system is one with a smaller storage and one where there is overflow during part of the year. Many times, significant cost savings are realized when using locally available materials. There are many publications that describe various techniques. The designer, installer, and user of water harvesting should become as familiar as possible with all techniques, and use the approach that is best suited to local conditions.

Runoff Farming - Water Spreading:

The available literature describing techniques for runoff farming/water spreading is usually not as accessible. Much of the information is developed by trial and error, and only brief descriptions are presented in proceedings of meetings. Very little information reaches the scientific journals. There are some basic relations concerning factors such as runoff characteristics, soil properties, plant water requirements, and climatic variations that should be considered. The more familiar the user is with the relations, the better the chances of success.

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