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TECHNICAL, ECONOMIC, AND SOCIAL CONSIDERATIONS OF WATER HARVESTING AND RUNOFF FARMING

Gary W. Frasier

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University of Arizona
Tucson, Arizona

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ABSTRACT

Water harvesting, the collection and storage of precipitation runoff from a prepared area, is a method of water supply that can be developed in areas where other water sources are not available. A water-harvesting system is composed of a water collection area, (catchment), a water storage facility, and other components such as piping, evaporation control and fencing. Based on the ultimate use of the water, there are two general types of water-harvesting systems; [1] drinking water systems, and [2] crop growing (runoff farming) systems. Even though the two types are quite different, the same general design procedures are used on all systems.

No universal, single method or system is best suited for all sites or water needs. Each site has unique characteristics that will affect the design of the optimum system. Variability of climate, soils, topography, and water needs require that each system be specifically designed to match the local conditions.

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INTRODUCTION

The term "water harvesting" is used to describe the process of collecting and storing water from an area that has been treated or covered to increase precipitation runoff. The 'harvested' water is stored in a suitable container for later uses such as drinking water supplies for man and animals or for the supplemental irrigation of crops. A 'water-harvesting system' is the complete facility for collecting and storing the runoff water. The 'catchment area' is the component of the water-harvesting system that collects and concentrates the precipitation. The 'storage facility' is the component of the water-harvesting system that stores the water until the time of need. Each water-harvesting facility has various peripheral items such as sediment or trash traps, evaporation control, and fencing. Water harvesting is not an inexpensive method of water supply, but it does have the potential of supplying water to any area where precipitation occurs. There is no "best" or "standard type or size of water-harvesting system. This paper presents some general design considerations and concepts that are potentially feasible for installing a water-harvesting system in any part of the world.

DESIGN FACTORS

There are two general types of water-harvesting systems, based upon the use of the collected water. One type is used to supply drinking water for man and animals. The other type, 'runoff farming', is used to provide water for the growing of crops. There are both similarities and differences between the two types, but many of the same general design procedures are used for both types. Variability between sites in climate, soils, land topography, water use, and water requirements necessitates that each system be specifically designed to fit the local site conditions.

Water Requirements

The water-harvesting system, plus any temporary water sources, must supply the total quantity of water required and satisfy any seasonal distribution requirements. These requirements vary for each installation. For systems supplying animal drinking water, the total water requirements are based on the type and numbers of animals using the area. The quantity of water for domestic household use will depend upon the number of people, uses of the water, and the amount of water conservation practiced. Table 1 gives some estimates of daily water requirement for domestic use and drinking water supplies. For many domestic and livestock supply systems, the water requirements may remain relatively constant throughout the year, but there are range management practices, such as rotational grazing, where the water requirement is non-uniform during the year and maybe even between years.

For runoff farming applications the total water requirement can be estimated from total consumptive water use data. Table 2 presents some consumptive use data for selected irrigated crops. The values listed are the quantities of water per unit area required for maximum production with irrigation. The plants will survive with less water, but there will be a reduction in plant production or yield. The timing of the water is also important. Figure 1 is an example of the seasonal distribution of water for a crop of barley. The total seasonal 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.

Seepage or evaporative water losses from the storage are non-beneficial water uses that must be included as part of the total water requirement. In hot arid climates, evaporation losses from an open water surface can be as high as 2 to 3 meters per year. Seepage losses from a "sealed" earthen tank can equal the water lost by evaporation, resulting in a total loss in excess of 6 meters per year. In some installations the seepage and evaporative losses exceed the quantity of water required for beneficial use. Failure to include these losses as part of the water requirement can result in an undersized system and insufficient water during critical periods.

Precipitation

The quantity of precipitation which will occur during a given time period is one of the most difficult parameters to accurately predict. Monthly averages are the most common data base but, short-term fluctuations from the mean can significantly affect the overall effectiveness of a water-harvesting system. It is desirable to use a minimum of 10 years of data for determining the mean. If there are extreme variations between years, it may be desirable to utilize a conservative system design to insure that there are adequate quantities of water in the majority of the years. This can be accomplished by eliminating the data from the two wettest years. In some locations where long-term data are available, probability analysis can be utilized in estimating precipitation quantities and frequencies. 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.

Availability of Materials and Labor

There is no best material for a catchment and storage. Usually, the facility is constructed as much as possible with locally available materials. One must balance the cost of materials to the cost of labor used in construction. Some materials and installation techniques are labor intensive, but have a relatively low capital cost. Other installations may have high materials cost, but low labor requirements.

Acceptance and Need as Viewed by User

The user of a water supply system must be involved in the planning and construction process as much as possible. The success and performance of the system will depend upon the user for the proper operation and maintenance. The user must believe that the system is the best for his purpose or situation, otherwise, the required operational procedures may not be followed. 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 will require minimal maintenance. If the user has been shown that the ideas are valid, there is a greater probability that the proper operation and maintenance procedures will be followed. Once the user is assured or convinced that the system will supply the required quantities of water, it may be possible on future installations to use systems or materials that are as effective but may have higher maintenance requirements.

CATCHMENT TREATMENTS

There are many ways that a catchment area can be modified to increase precipitation runoff. These can be grouped into three general categories: [1] topography modifications, [2] soil modification, and [3] impermeable coverings or membranes. In many installations, a catchment treatment will be a combination such as soil smoothing (topography modification) and waterproofing (soil modification). All treatments do not necessarily have the same runoff efficiency or effective life (1). Table 3 lists some of the more common catchment treatments, with an estimate of the runoff efficiency, treatment life and materials cost for installation. In most installations, the total cost estimates should also include any re-treatment costs plus yearly interest charges and maintenance costs based on the expected life of the treatments.

Topography Modifications

One of the simplest examples of topography modification is the construction of water collection channels at the outfall of rock outcroppings. Small masonry dams on the lower edge of rock areas can provide relatively large quantities of water with a minimum of materials and labor. Rock surface catchments and hillside areas cleared of brush and rocks to increase the rate of runoff were the earliest forms of water harvesting (2). They are still a valid means of water collection in some areas. The 3,500 'roaded' catchments comprising a total area in excess of 5,000 hectares in Western Australia are a form of topography modified catchments (3).

Topography modification is a low initial cost treatment, but it is not suited for all 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 (4). The average runoff efficiency of a topography modified catchment may be relatively low and there is frequently a relatively high 'threshold' rainfall, or quantity of precipitation required to initiate runoff.

Soil Modifications

Soil modification treatments consist of chemicals sprayed on the soil surface or mixed into the soil to reduce, or stop, water infiltration. One low cost soil treatment is sodium dispersed clay or salt treatment. A sodium salt (ie.common table salt, (sodium chloride) [NaCl]; soda ash, (sodium carbonate) [Na CO]) is mixed into or sprayed onto the soil surface. When the soil becomes wetted the sodium disperses the clay aggregates and plugs the soil pores or forms impermeable clay lenses which reduce the rate of water movement through the soil profile (5). On some soils, erosion may be a problem. Average runoff efficiency for design purposes is 50- 80%.

A second type of soil modification consists of applying a hydrophobic chemical which causes the soil particles on the catchment surface to become water repellent. These treatments usually do not provide any lasting change to the soil porosity or improvement in stability. Instead, the waterproofing is caused by changing the surface tension characteristics between the water and the soil particles. Two water repellent materials that have been used in limited installations are; [1] a water-based sodium silanolate (silicone), and [2] molten refined paraffin wax. The silicone treatment is simple to apply by spraying but it forms a very thin waterproof layer that is susceptible to erosion. The treatment is not suited for soils containing over 15% clay. Effective treatment life is 3-5 years with runoff efficiencies of 60 - 95% (6). The paraffin wax treatment consists of spraying a low melting point wax, (ie. 50 C), onto the soil surface (7). The wax is initially deposited as a thin layer on the soil surface. As the sun warms the soil surface above the melting point of the wax, the wax migrates deeper into the soil, covering each soil particle with a thin wax coating. This treatment is not suited for soils containing over 20% clay and must be used on catchment sites where the surface soil temperatures will exceed the melting point of the wax during some part of the year (8). The effective treatment life on suitable soils is probably in excess of 10 years with an average runoff efficiency of 70-95%.

The third type of soil modification treatment consists of applying bitumen or asphaltic materials to the catchment surface. Many installations with these treatments were unsatisfactory because of inadequate waterproofing and durability to justify the cost. There have been limited successful treatments on fine, sandy soils for periods of 2 - 5 years. Typical runoff efficiencies are 50 - 90% (9).

Impermeable Coverings or Membranes

Most types of plastic and other types of thin films or sheetings have been investigated as potential soil covering treatments. Many of these materials, when exposed, are susceptible to mechanical damage or sunlight deterioration (10). Covering thin sheetings of plastic or roofing tar paper with a shallow layer of clean gravel can reduce these problems. The sheeting is the waterproof membrane and the gravel protects the sheeting from mechanical and photochemical damage. This treatment requires a good periodic maintenance program to insure that the gravel covering remains in place. Runoff is essentially 100% after the threshold rainfall, (approximately 2 mm), has been exceeded. Windblown dust, trapped in the gravel layer forming a seedbed for plants, has been a minor problem (11).

A covering composed of a random weave fiberglass or synthetic polyester filter fabric matting impregnated with an asphalt emulsion, has been a successful treatment. The matting is unrolled on the prepared catchment surface and saturated with the asphalt. Three to 10 days later a final sealcoat of asphalt emulsion is brushed on the membrane. With proper maintenance and periodic re-coating, the runoff efficiency from the asphalt-fabric treatment is 85-95% with an expected life of 10-20 years (12).

Most conventional materials such as sheetmetal, concrete and artificial rubber sheetings have been used as catchment treatments. These materials are relatively expensive, but when properly installed and maintained, have long lives and may be the best treatment for some locations (13,14). These treatments also require a maintenance program. For example, all cracks and expansion joints in a concrete catchment area must be periodically filled with some type of sealer.

WATER STORAGE TECHNIQUES

Water storage facilities can be separated into two general groups: [1] the soil profile or monolith, and [2] tanks or ponds. The tanks may be above the ground surface or buried into the ground. The type of storage selected depends upon factors such as; the ultimate use of the water, site topography, availability of materials and labor, etc.

Soil Monolith Storages

In many runoff farming installations, the soil profile (monolith) within the crop growing area is the water storage container. Some primary factors that must be considered in designing monolith storages are, [1] the depth of soil profile, [2] water holding capacity of the soil, and [3] the water infiltration rate of the soil profile. Shallow soil profiles will not have sufficient water holding capacity and may restrict root growth. In deep soil profiles, water may be lost by deep percolation below the plant zone. Sandy or coarse textured soils have a high infiltration rate but also a low water-holding capacity which limits the quantity of water that can be stored in the root zone. Conversely, fine textured soils can store a greater quantity of water, but have slower water infiltration rates. Very fine soils may not be suitable because of excessively slow infiltration rates. Except for very low rainfall intensities, the rate of runoff from the catchment area will exceed the infiltration rate into the soil. This requires that provisions be made for temporarily ponding or holding the collected water on the infiltration or crop area for a sufficient time to allow the water to percolate into the soil.

Tank or Pond Storages

External water storage facilities are an essential component of any drinking water system. They may also be a part of a runoff farming system, by providing either the entire water storage facility, or serving as a supplemental storage to the soil profile. Any container capable of holding the water until it is needed, is a potential water storage facility. Unlined earthen pits or ponds are usually poor methods of water storage unless seepage losses are controlled. Typical seepage control measures include installing liners of plastic or artificial rubber, or chemically sealing the soil. Exposed liners are susceptible to damage by animals, wind and sun and should not be used unless there is a good periodic maintenance program (15). Liners can be effective in some installations if they are protected by a soil cover. On some soil types, earthen ponds can be sealed by mixing a sodium salt into the soil (16).

There is an almost unlimited number of types, shapes, and sizes of wooden, metal, and reinforced plastic storage tanks. Cost and availability are the primary factors which determine the potential suitability of these storages. One common type of storage is a steel rim tank with a concrete bottom or some other type of impermeable liner or bottom (17). Another storage which has a low materials cost is a plastered concrete tank. This storage does require a significant amount of hand labor for construction (18). In many water-harvesting systems, the water storage facility is the most expensive single item and may represent over 50% of the total system cost.

Evaporation control is a necessary component of every water storage facility and one of the most economical approach for maintaining adequate water supplies. Evaporation control on storages with sloping sides is difficult because of the change in water surface area with depth. Roofs over the storage are a common effective method, but they are relatively expensive (11). Floating covers of low-density synthetic foam rubber are effective on vertical walled, open topped storages (19).

RUNOFF FARMING SYSTEMS:

There are two basic types of runoff farming systems, [1] direct water application, and [2] supplemental water. In the direct water application system the runoff water is stored in the soil profile. In the supplemental water system the water is stored off-site and applied to the crop with some form of an irrigation system. In practice, some installations are a combination of the two types.

Direct Water System

In the direct water system, the collected runoff water is diverted to the crop area for direct infiltration into the soil. Dikes or ridges around the crop area are necessary to retain the water until it infiltrates into the soil. With this type of system it is not possible to change the frequency or timing of water application, only the quantity of water which is infiltrated into the soil is changed. Water is applied to the area only during the precipitation event. Varying the catchment area size and/or catchment runoff efficiency will change the quantity of water applied to the crop, but water is applied only during the precipitation event.

Water spreading, the diversion of water from channels or upslope areas onto the crop growing area, is a form of direct water system that frequently encompasses relatively large areas. Storm runoff water is diverted from a channel or area by a series of dikes or diversion banks and spread across the crop growing area. Most water spreading systems in use today have evolved over a period of years by trial and error methods.

Many direct runoff farming systems are composed of small prepared catchments directly upslope of the crop growing area. These systems are effective for use in growing shrubs or trees. Ratios of run-off to run-on areas are typically 1:1 to 20:1 depending upon the soil type, plant type, expected precipitation intensities and quantities, and the infiltration characteristics of the soil profile. Catchment areas range from irregular shaped areas with minimal site preparation and soil treatment, to graded, compacted areas that are sealed to maximize the runoff efficiency.

Supplemental Water Systems

In supplemental water systems the collected water is stored adjacent to the growing area in a tank or pond for later application to the crop with some form of an irrigation system. One major advantage of these systems is the capability of supplying water to the crop at the time of need. The extra cost of providing the required water storage and irrigation facilities is a disadvantage. If the catchment area and storages are located upslope of the crop area, simple surface irrigation systems can be utilized. Within the past decade, drip or trickle irrigation systems have been used for applying the water. These systems are expensive to install but have a high water use efficiency with very little water loss from deep percolation and/or evaporation from the soil surface.

Combination Systems

As the name implies, these systems are a combination of the direct water and supplemental water techniques. The runoff water from the catchment area flows across the crop growing area and some of the water infiltrates into the soil profile. The excess water flows into a storage facility for later application by some form of irrigation system, such as a trickle irrigation pump back system (20).

WATER HARVESTING SYSTEM DESIGN

For most installations, there will be several combinations of catchment and storage sizes which will provide the required quantities of water. Since water storage is one of the single most costly items, the lowest total-cost water-harvesting system will frequently be one with a reduced storage volume. With these systems there may be some water lost by storage overflow during some periods. Frasier and Myers (11) presented a description of a procedure where the optimum catchment and storage tank sizes for drinking water supply systems can be determined by a series of hand calculations or with a programable desk-top calculator.

Example-Design of an Animal Drinking Water System

Additional livestock and wildlife drinking water supplies are needed on a ranch near Williams, Arizona. Sixty cows use the area for 5 months (Nov-Dec and Mar-May) and 30 deer use the facility yearlong. The cattle require 40 liters/head/day and the deer use 8 liters/head/day (Table 1). The catchment treatment selected is an asphalt-fabric membrane costing $3/sq.meter with a runoff efficiency of 95%. The storage is a steel-rim tank with a concrete bottom and a floating foamed rubber cover. Total unit storage costs are $37/1000 liters. Table 4 presents the precipitation and water requirements for the problem. The optimum size combination of catchment and storage are estimated using the monthly water balance procedure of Frasier and Myers (11). Figure 2 shows the sizes of catchment and storage and the costs of 7 different combinations which will provide the necessary water. Size combinations 2 to 5 have the lowest total system costs. The user would decide which of the combinations is best suited for his operation.

Example-Design of a Runoff-Farming System

A crop of barley is to be grown with runoff farming techniques near Tucson, Arizona. The soil of the area is an Anthony sandy loam (Typic torrifluvent, coarse loam, mixed, calcarious thermic) (21) with a bulk density of 1.65 and water holding capacity of; 1/3 bar = 18% by weight, 15 bar =4% by weight. This converts to a useable water holding capacity of approximately 2.3 mm per cm of depth. The expected rainfall from the Tucson area and the water requirements of barley as determined from the consumptive use data (Figure 1) is presented in Table 5. Various runoff:runon area ratios and soil depth combinations were estimated using a monthly water balance procedure. Figure 3 shows the relationship of the ratio of the catchment or runoff area:crop or runon area to the total water storage volume required per unit crop area for catchment runoff efficiencies of 50, 70 and 90 percent. The scale at the top of the figure represents the depth of soil at the site that would be required to provide the necessary storage volume. The user would have to decide which of the soil depths would be representative of the site and the rooting zone of the barley, and which runoff efficiency was economically feasible. With these estimates, it is possible to select the proper sized runoff area which would provide the required soil water. These estimates are conservative because the crop growing area will receive some water directly during the precipitation event. This approach does not include any adjustment for variabilities that might occur in precipitation quantities or frequency between years or the water requirement for seed germination and seedling establishment.

SUMMARY

Water-harvesting, runoff-farming systems are technically sound methods of water supply for most parts of the world. There is no universally best system of water harvesting or runoff farming. Each site has unique characteristics that will influence the design of the optimum system. Any impervious area or surface is a potential catchment surface. The major cost item of a drinking water supply system is the cost of the water storage facility. Often the most cost effective system is one where there is overflow during part of the year. In addition to the total annual water requirement there is also a seasonal distribution of the required water that must be satisfied by the water-harvesting system. This is critical in the design of a runoff-farming system for the growing of crops. 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 for the local conditions.

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FIGURE LEGENDS

Figure 1 - Mean consumptive water use for barley at Mesa, Arizona for the years 1952-53, 1969-70 (22)

Figure 2 - Relative sizes and costs of 7 different combinations of catchment areas and storage volumes of a water-harvesting system for supplying livestock and wildlife drinking water Example - Design of Animal Drinking Water System.

Figure 3 - Relative runoff-to-runon ratios and soil storage capacity required for growing barley near Tucson, Arizona. Example - Design of a Runoff-Farming System.

Table 1. Estimates of daily water requirements for domestic use and animal drinking water (11)

Use	Daily water requirements
	Liters/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

Table 2. Consumptive use water requirements for selected crops (22)

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 panicgrass	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 3. Water-harvesting catchment treatments (23)

Treatment	Runoff efficiency	Estimated life	Materials initial cost 1/
	(%)	(years)	($/sq.m)
TOPOGRAPHY MODIFICATIONS:			
Land smoothing and clearing	20 - 35	5 - 10	0.05 - 0.20
SOIL MODIFICATIONS:			
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
IMPERMEABLE COVERINGS:			
Gravel covered sheetings	75 - 95	10 - 20	1.00 - 1.75
Asphalt-fabric membranes	85 - 95	10 - 20	1.75 - 3.00
Concrete, sheetmetal, artificial rubber	60 - 95	10 - 20	5.00 -20.00

1/ Adjusted to 1983 material costs

Table 4. Precipitation and animal drinking water requirements for 60 cows and 30 deer near Williams, Arizona for drinking water design example (11)

Month	Precipitation	Water Requirement	Month	Precipitation	Water Requirement
	1/ (mm)	(liters)		1/ (mm)	(liters)
Jan	48	7200	Jul	68	7200
Feb	48	7200	Aug	74	7200
Mar	44	80000	Sep	35	7200
Apr	33	80000	Oct	31	7200
May	15	80000	Nov	27	80000
Jun	11	7200	Dec	48	80000

1/ Williams, Arizona precipitation adjusted for runoff efficiency of 95%

Table 5. Precipitation and water requirements for growing barley near Tucson, Arizona in runoff farming example.

Month	Precipitation 1/	Water Requirement 2/	Month	Precipitation 1/	Water Requirement 2/
	(mm)	(mm)		(mm)	(mm)
Jan	22	38	Jul	53	0
Feb	20	85	Aug	53	0
Mar	18	193	Sep	29	0
Apr	10	247	Oct	15	0
May	5	45	Nov	21	4
Jun	7	0	Dec	24	23

1/ Long term mean from Tucson, Arizona
2/ From (22)

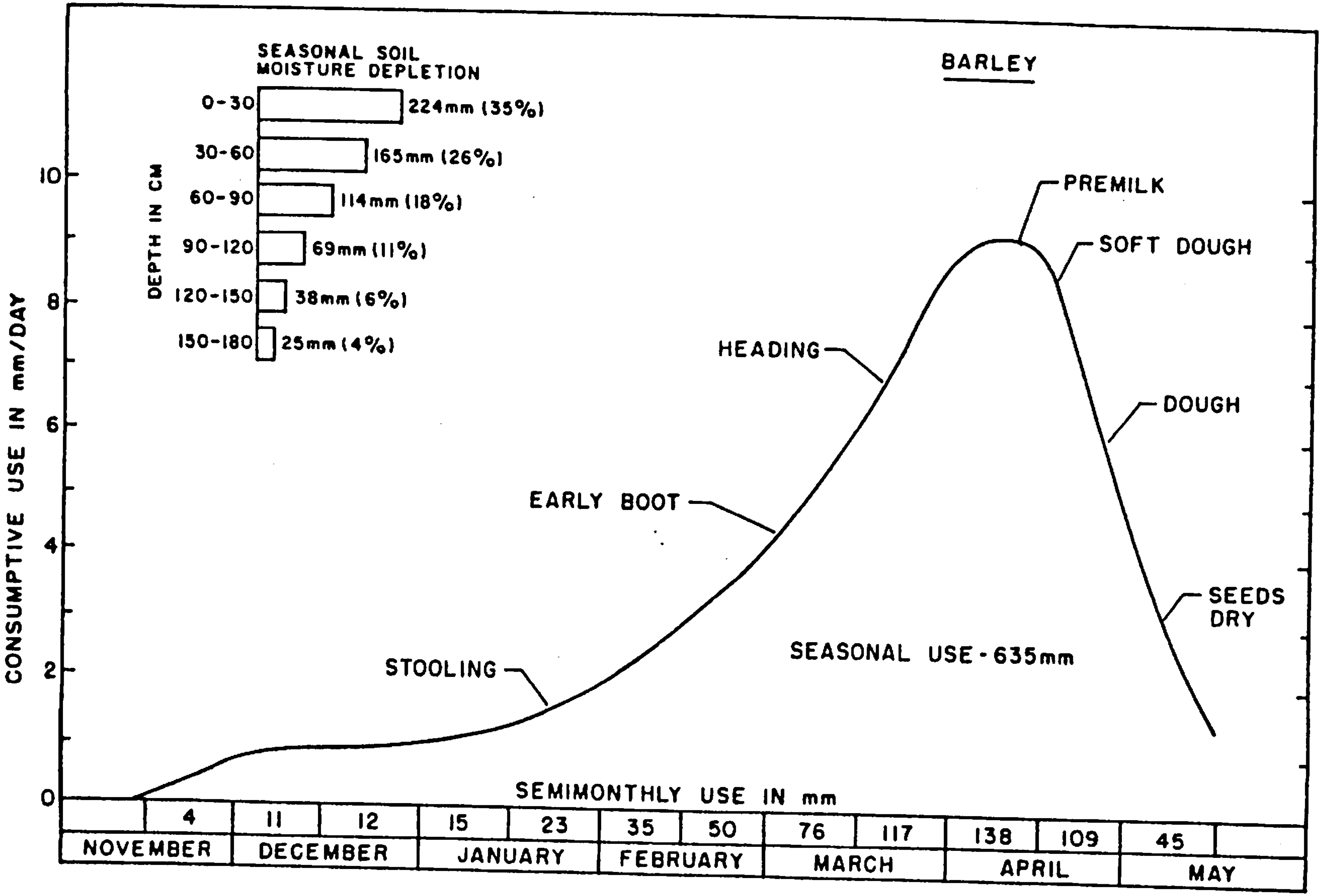

Figure 1 - Mean consumptive water use for barley at Mesa, Arizona for the years 1952-53, 1969-70 (22)

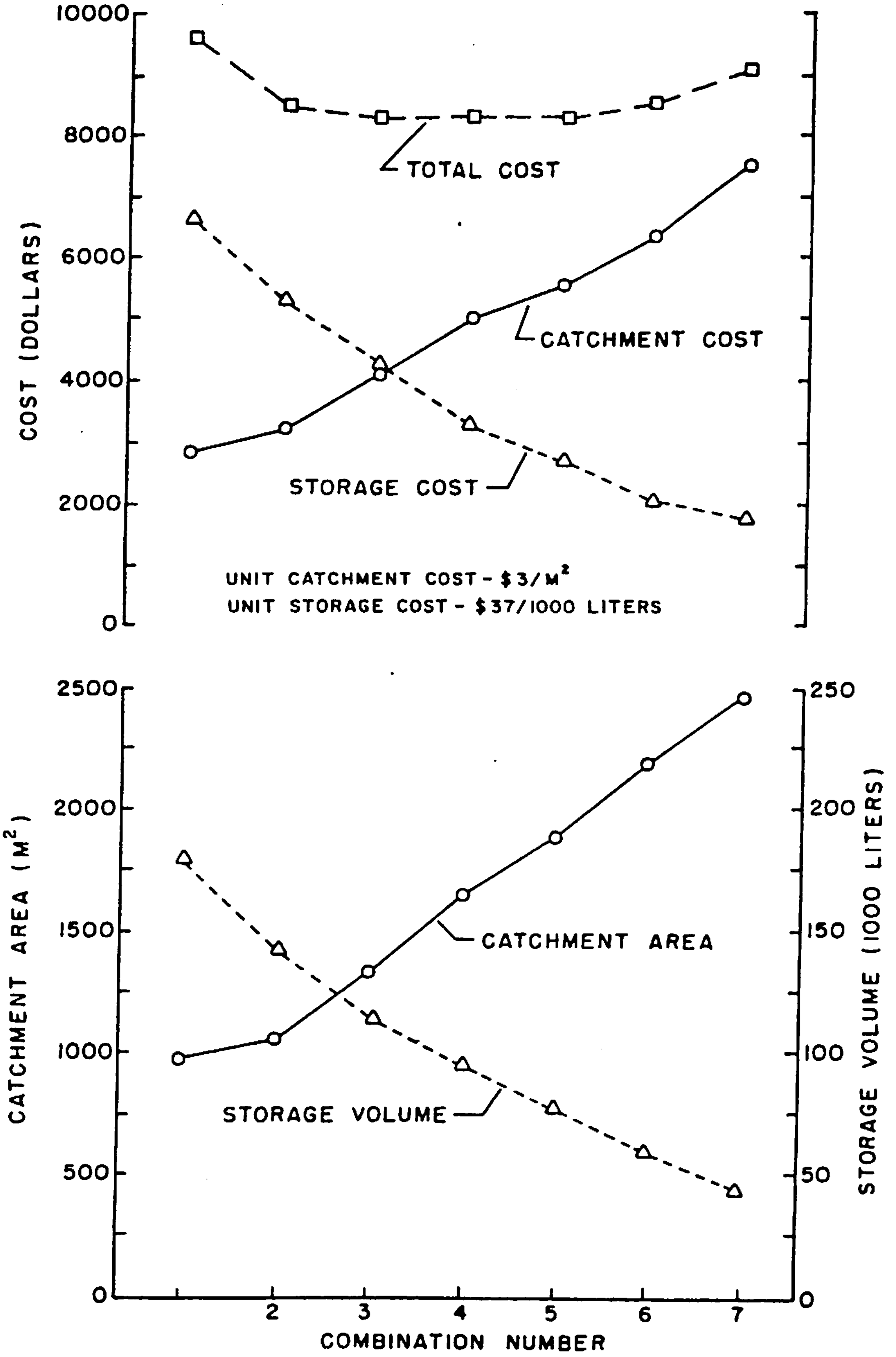

Figure 2 - Relative sizes and costs of 7 different combinations of catchment areas and storage volumes of a water-harvesting system for supplying livestock and wildlife drinking water Example - Design of Animal Drinking Water System.

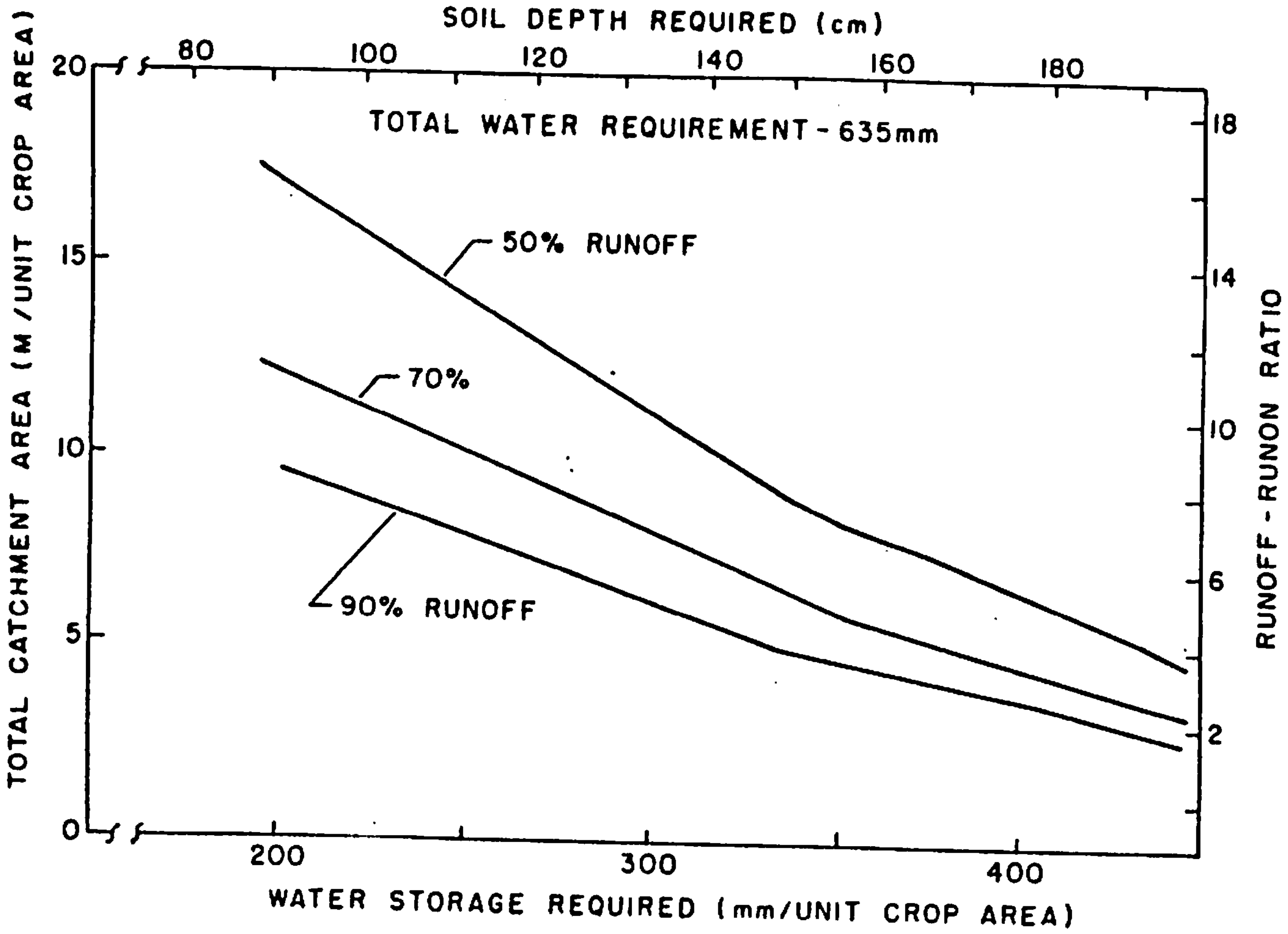

Figure 3 - Relative runoff-to-runon ratios and soil storage capacity required for growing barley near Tucson, Arizona. Example - Design of a Runoff-Farming System.