WATER HARVESTING TECHNOLOGY APPLICABLE TO SEMIARID, SUBTROPICAL CLIMATES

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A. WATER HARVESTING BY SURFACE TREATMENT

1. Introduction

Water harvesting using surface topography is the process of collecting and storing, or harvesting, precipitation from an area that has been treated to increase the runoff of rainfall and snowmelt [2]. Water harvesting using subsurface soil strata for storage and supply is the process of trapping precipitation or the runoff of rainfall and snowmelt by construction of artificial spring aquifers at strategic sites of a selected watershed [7]. We will consider first water harvesting by surface treatment.

The use of surface methods dates back about 4,000 years to some of the Middle Bronze civilizations. These farmers cleared hillsides of rock and gravel to smooth the soil and increase runoff. Contour ditches were dug on the hillsides to collect the water and carry it to lower-lying fields where it was used to irrigate crops. Even though these runoff farming systems had many faults, they permitted the development of agriucltural civilizations in a region having an average annual rainfall of about 100 mm.

Collection and storage of runoff from the roofs of houses is an old practice that is still used in some regions, although the development of central water supply systems has caused it to be abandoned and forgotten in many parts of the world. Some catchments have been built in the form of roofs without a house under them [23]. A. S. Kenyon [17] describes such a 2,420 m^2 catchment built of galvanized sheet iron at a location in Australia having 300 mm average annual rainfall. Even during the lowest rainfall years this catchment provided adequate water for "6 persons, 10 horses, 2 cows, and 150 sheep."

During the past 60 years, a limited number of artificial catchments have been built, usually on islands where runoff from porous soils is low despite high rainfall. Very few have been built in arid regions, and most of these have been built at high cost by government agencies to collect water for livestock and wildlife. Construction materials have consisted of sheet metal, concrete, asphaltic concrete, soil cement, and asphalt impregnated fiber planking.

The potential benefit of water harvesting can be illustrated by reporting rainfall as a volume rather than as depth. One millimeter of rain equals one liter of water per square meter. It becomes apparent that a small area of impermeable material can collect a relatively large volume of water. Research to date has related primarily to improved methods and materials for catchment construction. Some of the more recent developments are briefly summarized in the following paragraphs. These include <u>smoothed soil</u>, <u>sodium salts</u>, <u>hydrophobic soil</u>, <u>sprayed asphalt</u>, <u>plastic and metal film</u> and <u>synthetic membranes</u>.

2. <u>Experimental Studies</u>

a. The simplest artificial water harvesting structure is a <u>cleared</u>, <u>smooth soil surface</u>. Hillel et al. [15], working with a well-aggregated, permeable clay-loam soil having a slope of 4 percent, found that clearing and smoothing a small plot produced 21 percent runoff of 195 mm rainfall during the winter of 1965/66. Runoff from <u>natural soil surfaces</u> in the study area is about 5 percent [14]. Myers [23] working with a gravelly, sandy loam soil found that clearing and smoothing a 230 m^2 plot to a uniform slope of 5 percent resulted in runoff of 33 percent to 35 percent of the 170 mm to 395 mm rainfall during the years 1964 through 1966. No vegetation of any kind grew on the plot. Runoff from an adjacent, untreated 4,000 m^2 watershed was about 20 percent. Although the sandy loam soil alone is highly erosive, the natural soil surface is covered with a layer of fine gravel, called desert pavement. The gravel pavement reduced erosion to negligible amounts. These results indicate that significant runoff can be obtained from cleared, smooth soil surfaces when the soil is not excessively permeable. When erosion hazards are not excessive, and when large areas of low-cost land are available, this treatment may be the most economical method of water harvesting.

b. Sodium salts can be used to increase runoff from many soils. These salts cause clay in the soil to disperse or swell and partially seal the soil pores. Hillel [14] and his coworkers in Israel have obtained more than 70 percent runoff from sodium carbonate treatments of 45 kg per hectare, sprayed as a 10 percent solution in water on small plots of cleared and smoothed clay loam soil. Erosion was 2.9 kg per m^3 of runoff. Hillel [15] found that the salt was essentially lost after one year and retreatment was required. Cluff and Dutt [2] have treated a 4 hectare plot of vegetation covered sandy soil with 180 kg sodium chloride broadcast in powder form. They obtained 10 percent runoff from 73 mm precipitation. Erosion was not measured but visual observation indicated that erosion was not a problem. Although the use of sodium salts to increase runoff is low cost, several questions must be answered, including the durability of the treatment and erosion resulting from the treatment.

c. The treatment of soils by chemicals to make them hydrophobic was investigated by Davidson and Associates [8] as early as 1960. Such soils can give a high rate of runoff and offer excellent possibilities for low-cost, water-harvesting catchments. Myers [23] sprayed sodium rosinate at a rate of 27 kg per hectare on a test plot and found that the compound not only made the soil water repellent but stabilized the soil surface. However, he found that the material was rapidly destroyed by oxidation.

Other chemicals which have been tested include sodium methyl silicone, according to Meyers [23] reacts with calcium or magnesium in the soil to form an inert, water-repellent resin which is supposedly not biodegradable and is unaffected by temperatures up to 200°F. Spray application rates of 11.4 kg of active material per hectare on sandy loam soil caused the soil to become repellent to a depth of approximately 6 mm. A 230 m^2 plot of gravelly, sandy loam woil with a 5 percent slope produced over 94 percent runoff from a 243 mm rainfall. However erosion gradually caused ridges of gravel to form on the plot surface and removed the hydrophobic soil from about 8 percent of the plot surface. It has been found that materials used to stabilize hydrophobic soils cannot be used to stabilize water absorbent soils. The durability of the treatment will apparently depend upon the durability of the stabilizing material.

d. Laboratory and field experiments using <u>sprayed asphalt</u> as a water harvesting material were initiated at the U.S. Water Conservation Laboratory in 1959 [22] and continued until 1966. It was found that the best treatment consisted of applying two different asphalt materials. First a cutback asphalt, or bitumen in solvent, was sprayed on the soil to penetrate and make a strong but porous pavement. Second, a non-penetrating asphalt emulsion was sprayed on the pavement surface to seal the pores and to protect the base coat against deterioration by photo-oxidation. All of the pavements made in this way were in good condition after 2 to 4.5 years exposure to freezing and thawing, high summer temperatures, and high solar radiation. However, in regions of high solar radiation and low precipitation, runoff water was often colored by asphalt oxidation products. The coloration was not removed by filtering through sand and soil in the laboratory. A satisfactory method for prevention or removal of oxidized asphalt compounds should be developed before asphalt pavements are recommended for obtaining domestic water supplies. Asphalt catchments provide essentially 100 percent runoff.

e. Thin, plastic and metal films offer opportunities for building low-cost precipitation catchments except for the fact that they are easily destroyed by wind. Gravel-covered plastic film tested at the University of Arizona [23] demonstrated that gravel protects the underlying membrane against radiation and wind damage but retains part of the water which is then lost by evaporation. The amount of loss will depend on the size of gravel and the thickness of the gravel layer. Durability of these catchments should be good and they may be useful where gravel is readily available and maximum runoff is not required.

Aluminum foil bonded to smooth soil surfaces with asphalt was studied experimentally at the University of Arizona [23]. A 230 m^2 catchment near Phoenix, Arizona, was covered in 1962 with 1-mil aluminum foil bonded to the soil surface with cationic asphalt emulsion. The plot surface was not rolled smooth and was covered with fine gravel. Runoff was excellent for several years but declined to 72 percent by the third year. Wind problems were minor. Aluminum foil bonded to smooth soil with asphalt showed no sign of deterioration after 5 years of exposure.

f. In recent years there has been an accelerated use of synthetic membranes: polyethylene, vinyl and rubber. Lauritzen [19] using butyl rubber sheeting developed a combined catchment and water storage to collect and store water for livestock and wildlife. Reinforced butyl sheeting can be rapidly and easily laid over moderately rough surfaces, requiring only the removal of brush and sharp stones. Nylon reinforced sheeting has been successfully installed over sharp cinders, about 3 cm diameter, and on slopes up to 40 percent in Hawaii. Problems encountered in uplift of the sheeting by wind have been solved by eliminating changes in slope and by weighting the catchment surface with woil filled bags of butyl sheeting [23].

Polyethylene plastic is the cheapest, followed by vinyl, with rubber products the most expensive. The most popular rubber product at present is reinforced hypylon sheeting because of its economy and ease in field seaming [11]. On steep slopes plastic can be protected by using a thin layer of wire-reinforced mortars of approximately one inch in thickness. The mortar serves primarily to protect the plastic which provides the seepage barrier [3]. This is particularly important in constructing smaller compartmented reservoirs.

3. Compartmented Reservoirs

a. An obvious need in water harvesting by various surface treatments is the efficient storage of the entrapped water. Cluff [5] conducting studies at field sites near Tucson, Arizona; Goumbau, Mali; Nara, Mali; and San Francisco del Barreal, Coahuilla, Mexico, has successfully demonstrated the use of the compartmented reservoir as an efficient method of storing water in areas having relatively flat terrain where there is a significant water loss through evaporation. The flat terrain makes it difficult to avoid large surface-area-to-water ratios when using a conventional reservoir.

Figure 1 illustrates a three-compartmented reservoir as developed by Cluff. The tank consists of a receiving compartment which is called A. This compartment is located below the stream grade and therefore is usually shallow. Compartments B and C are shown as being smaller in surface area but deeper in depth.

Figure 2 shows that large water losses through evaporation can be reduced by compartmentalizing shallow impervious reservoirs and in flat terrain concentrating the water by pumping it from one compartment to another. Concentrating the water reduces the surface-area-to-water-volume ratio to a minimum, thus decreasing evaporation losses by reducing both the temperature and exposure of the water to the atmosphere. Portable, high-capacity pumps make the method economical for small reservoirs as well as for relatively large reservoirs.

A Compartmented Reservoir Optimization Program (CROP-76) was developed for selecting the optimal design configuration. The program was utilized in designing several systems. Through the use of the model, the interrelationship of the parameters have been elucidated. These parameters are volume, area, depth, and slope of the embankment around each compartment. These parameters interface with the parameters describing rainfall and hydrologic characteristics of the watershed.

The water-yield model used in CROP-76 requires inputs of watershed area, daily precipitation, daily and maximum depletion. In addition, three sets of seasonal modifying coefficients are required either through calibration or estimated by an experienced hydrologist. The model can determine runoff from two types of watersheds, a natural and/or treated

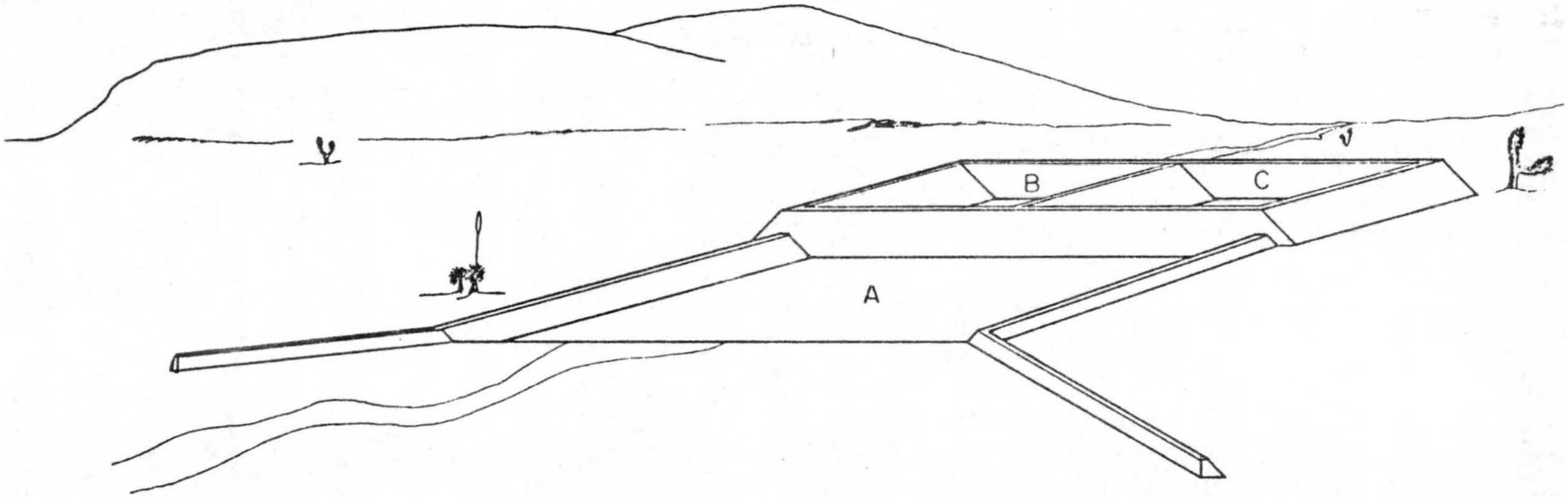


Figure 1. A Schematic Drawing of the Compartmented Reservoir (Cluff, 1977)

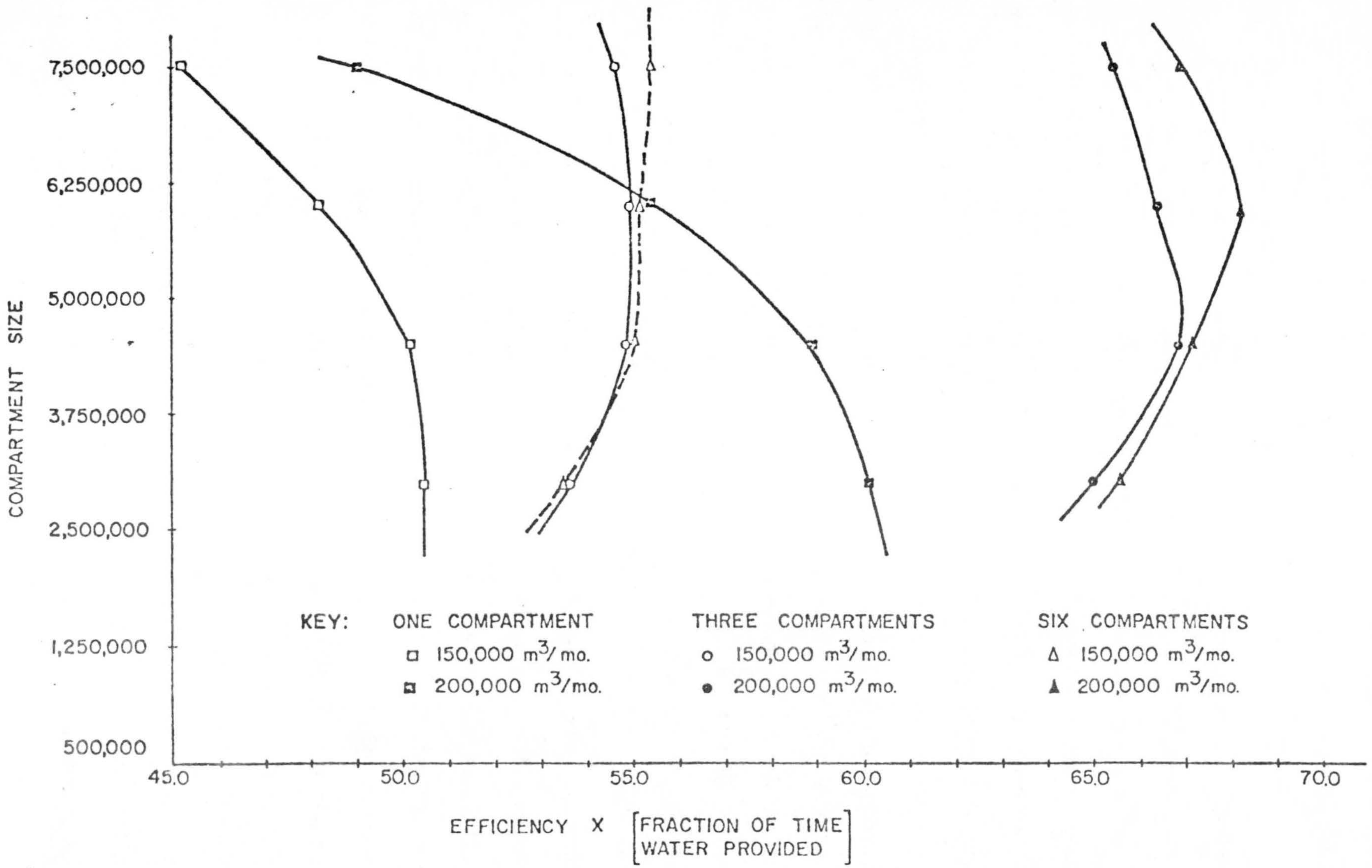


Figure 2. Compartment Size versus an Efficiency Factor for Compartmented Reservoir Systems, Nara, Mali (Cluff, 1977)

catchment. Additional inputs of CROP-76 are the surface water evaporation rate and the amount and type of consumptive use.

CROP-76 was used on several typical systems such as the small watershed at Goumbau, Mali (Fig. 3), the median-sized watershed at Nara, Mali (Fig. 4) and the water harvesting agrisystem at San Francisco del Barreal, Coahuilla, Mexico (Fig. 5). The following general observations were made: (1) The rate of increase of efficiency of storage decreases as the number of compartments increase; (2) there was no significant difference in evaporation loss by varying the relative size of compartments provided the side slope, depth, total number of compartments and the total combined volume remained constant; (3) the increase in efficiency due to use of the compartmented system decreases as the depth of the reservoir increases, becoming insignificant for depths of 20 or more meters; and (4) the use of compartmented reservoir provides efficient storage for a water harvesting agrisystem.

Shortly after the model was functional an opportunity arose to interface with a research project by Larsen et al. [18] involving ground-water pumping using solar energy. Larsen et al. [18] have shown that it is economically advantageous to pump into surface storage on an annual basis. The surface storage was used to match annual pumping to the more seasonal irrigation demand. The estimated pumping and irrigation demands for the 64-hectare project are shown in Fig. 6. Average weekly pumping and consumptive use values were input for a modified model. The water yield portion of the model was not used. Four years of monthly evaporation data were used to demonstrate the compartmented system. The initial storage and consumptive use were varied to reach an equilibrium over the four year period. A depth of six meters is suggested by

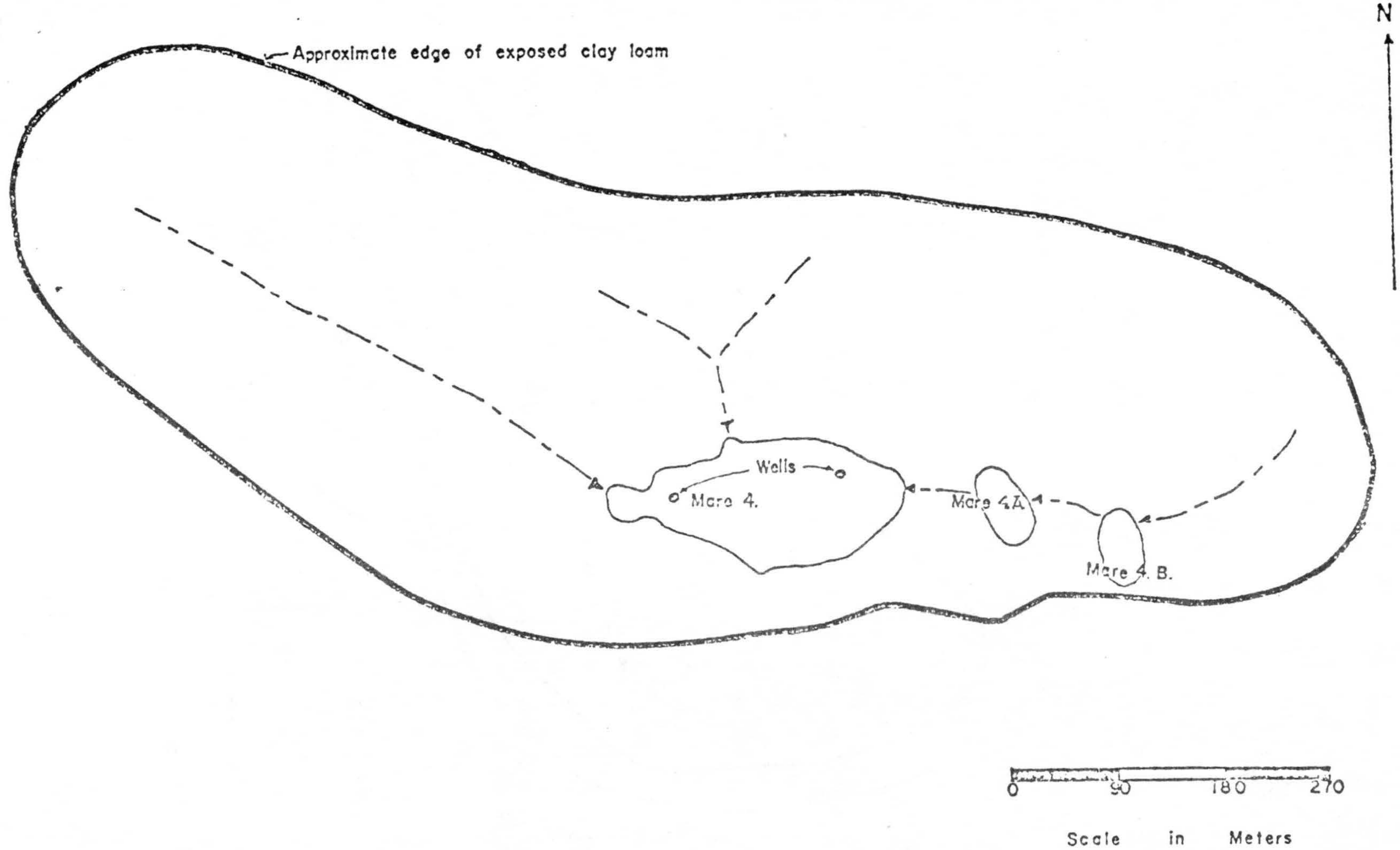


Figure 3. Schematic Map of Watershed of Mare 4 at Goumbau, Mali (Cluff, 1975)

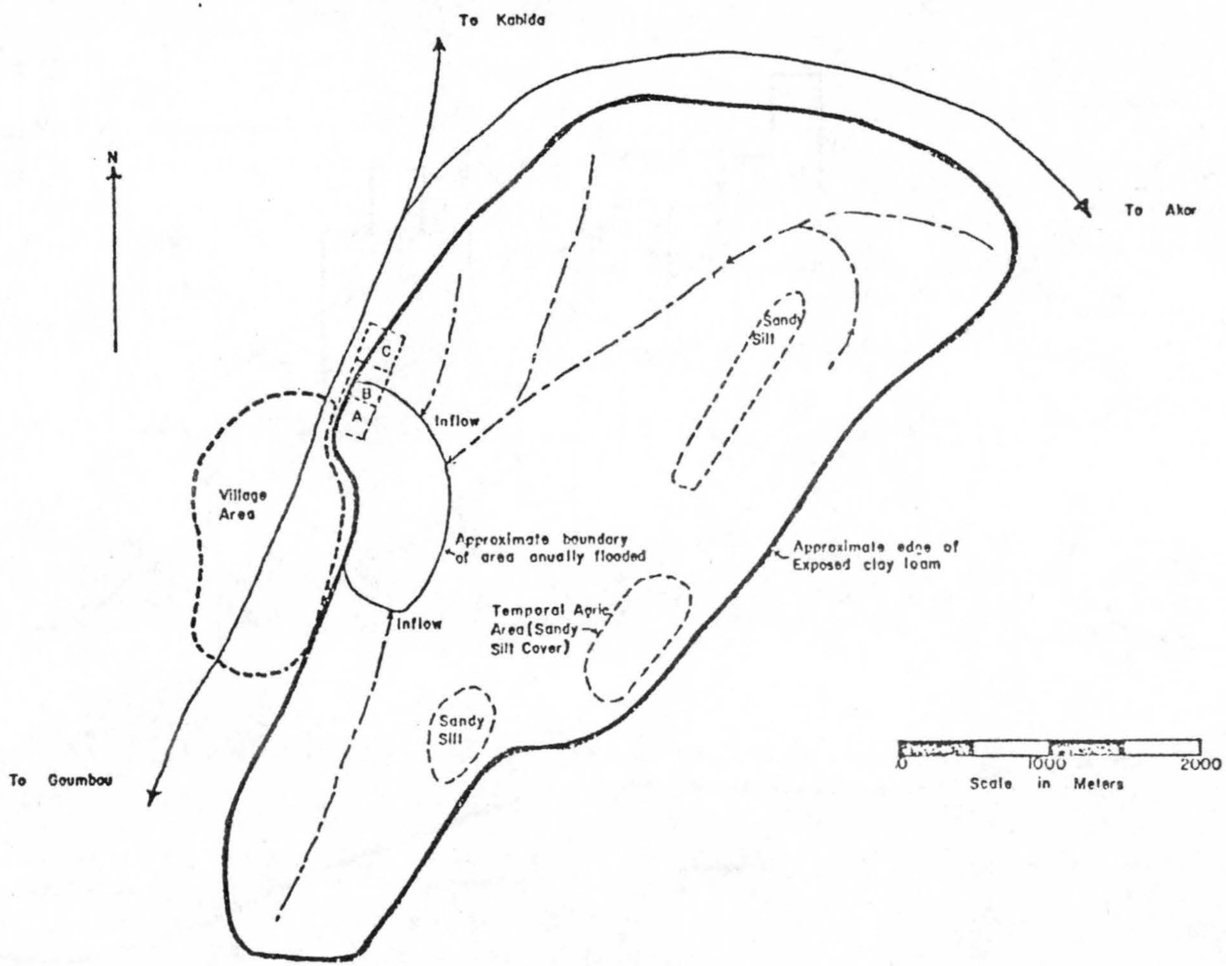
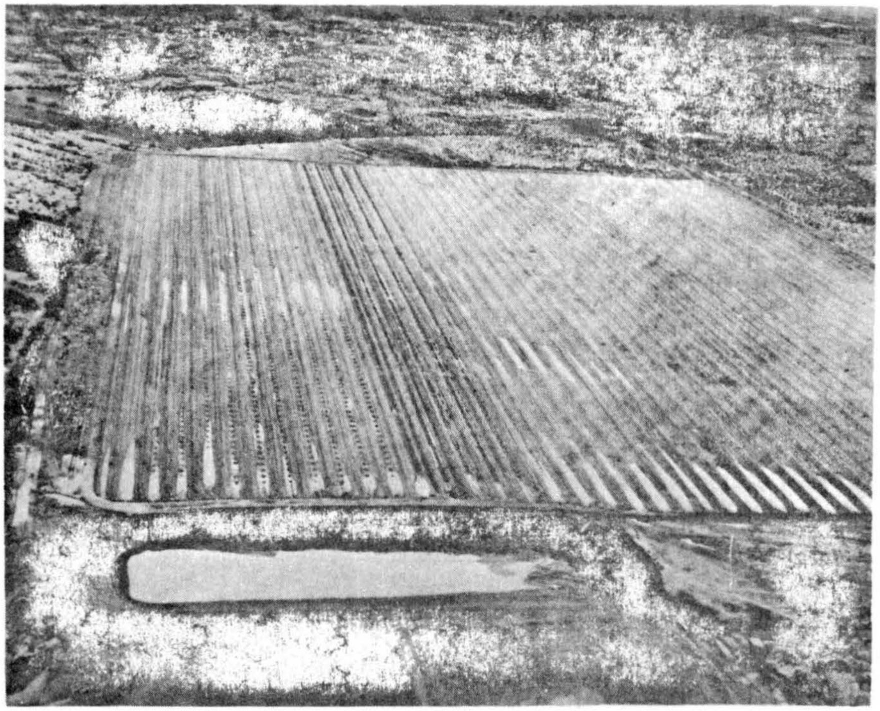


Figure 4. Outline of Nara Watershed Showing Location of Compartmented Reservoirs (Cluff, 1975)



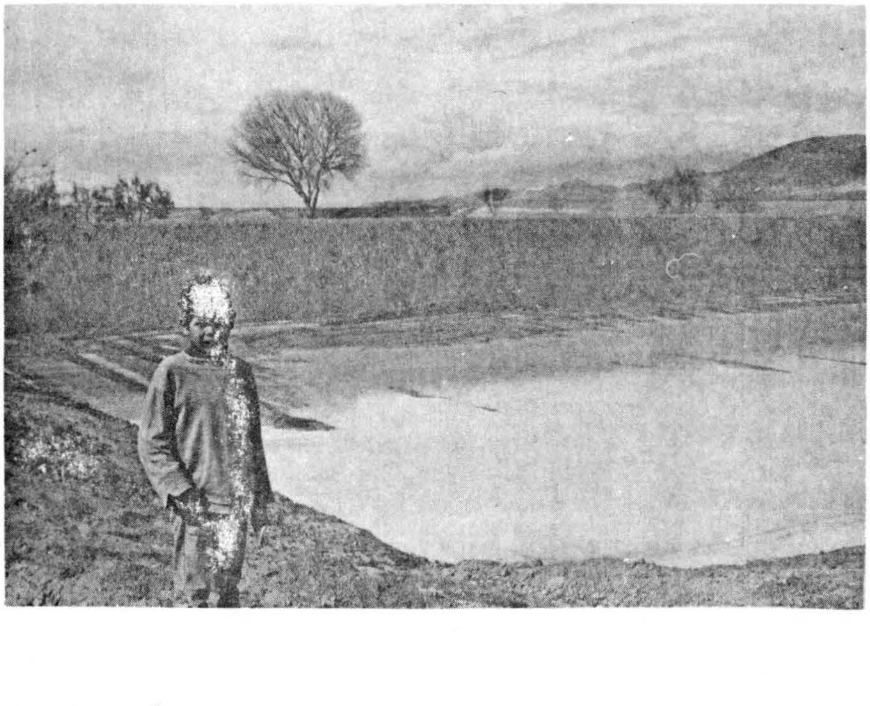


Figure 5. Twenty-Hectare Water Harvesting Agrisystem near San Francisco, Coahuilla, Mexico. -- Above: Aerial View of the Catchment during Construction. Below: The Compartmented Reservoir.

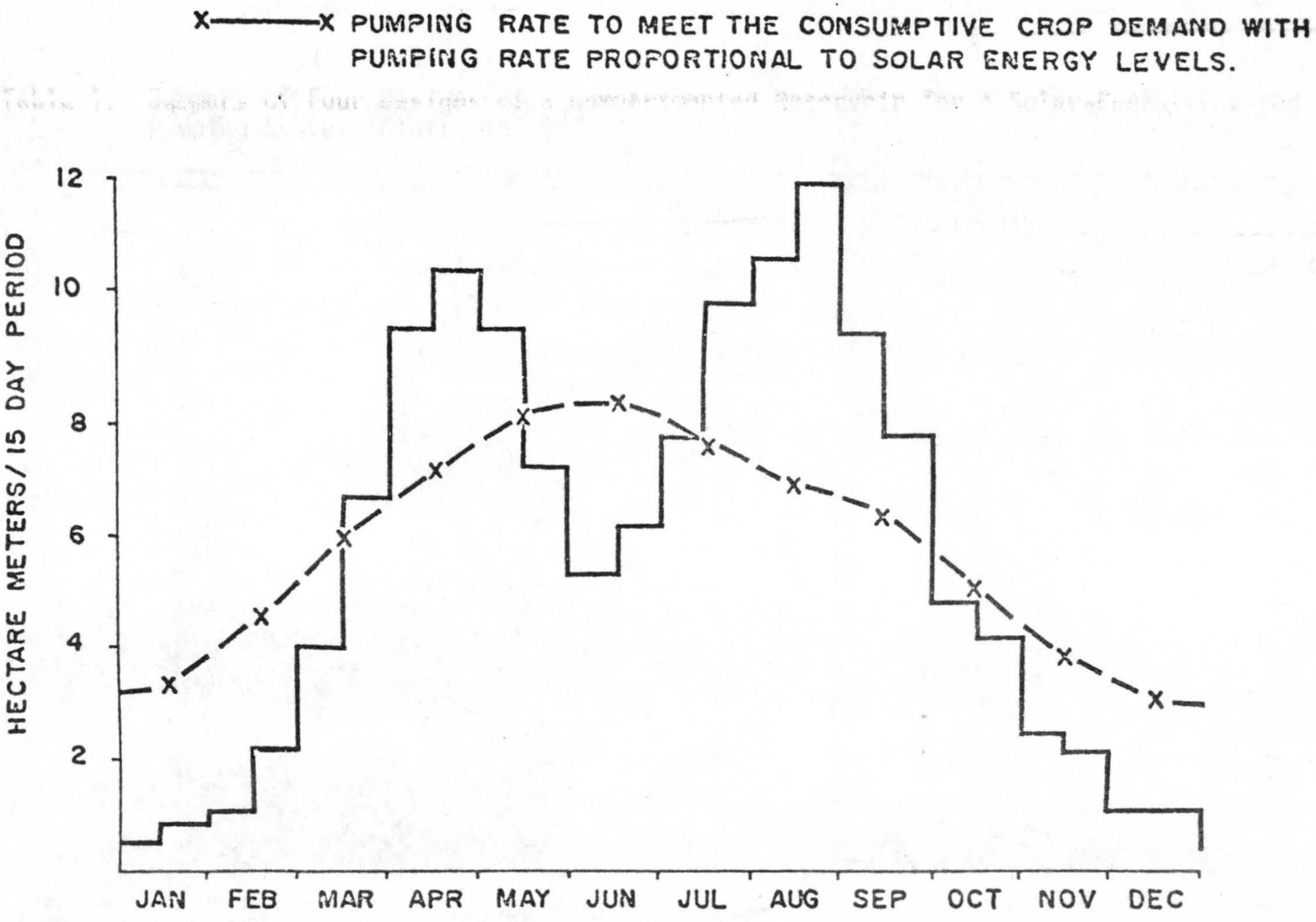


Figure 6. Matching Consumptive Demand from Water Storage where Pumping is Proportional to Solar Energy Input--Bar graph irrigation demand for 16 hectares each of cotton, lettuce, sorghum and alfalfa and 32 hectares of wheat grown on a 64-hectare (160-acre) farm near Mesa, Arizona (Larson et al., 1976)

Larsen et al. [18] as being realistic for this application. The use of a greater depth reduces the evaporation savings obtained when compartmenting the reservoir. In contrast, the use of a lesser depth would increase the importance of compartmenting.

Table 1, from Cluff [5], gives the result of the analysis made for four reservoir systems for storage of seasonally pumped ground water using solar energy. The table shows that there is a 30.3 percent and 37.5 percent evaporation savings resulting from the use of two and four compartments, respectively. There is a slight decrease in evaporation savings when the number of compartments is increased from four to eight; therefore, no more than a four-compartmented system is recommended.

A single compartment should cover 227 by 227 meters, or 5.15 hectares. A two-compartmented reservoir should cover 315 by 172 meters, or 5.42 hectares. The four-compartmented reservoir should cover 235 by 246 meters or 5.57 hectares. The single-compartmented reservoir requires 39,394 m^3 of embankment if the cut and fill were balanced. The four-compartmented reservoir requires 48,640 m^3, a difference of 9246 m^3. Three additional discharge pipes and valves are required in the four-compartmented system.

The amount of pumping required to keep the water concentrated also is given in Table 1. It is very small because solar-pumped water can be placed in any compartment to keep the water concentrated as much as possible. This reduces the need for auxiliary pumping as compared to the storage of floodwaters.

The use of a compartmented reservoir should significantly reduce evaporation loss. In addition, there are other advantages of a compartmented tank in this system. These are: (1) repair and maintenance is

Table 1. Summary of Four Designs of a Compartmented Reservoir for a Solar-Energy-Powered Pumping System (Cluff, 1975)

	Number of Compartments			
	One[1] (m^3)	Two[2] (m^3)	Four[3] (m^3)	Eight[4] (m^3)
Evaporation				
1967	68,715	47,705	41,196	40,756
1968	68,726	47,741	42,572	43,310
1969	70,576	49,326	45,085	45,756
1970	72,604	50,882	46,572	46,925
Total Evaporation	280,621	195,651	175,425	176,747
Average Evaporation	70,155	48,913	43,856	44,187
Consumptive Use[5]	1,295,851	1,303,651	1,319,251	1,319,251
Water Pumped	1,364,722	1,364,722	1,364,722	1,364,722
Change in Storage[6]	+3,897	-3,256	+2,183	+628
Amount Concentrated	0	0	6,802	5,036
% Evaporation Savings	-	30.3	37.5	37.0
% Storage Efficiency	94.95	95.52	96.67	96.67

[1] The capacity of the single reservoir is 205,000 m^3.

[2] The compartments are all 96,000 m^3.

[3] The compartments are all 48,000 m^3.

[4] The compartments are all 24,000 m^3. All compartments are rectangular with six-meter depths and 1:2 side slopes. The total volume of all compartmented systems is 192,000 m^3.

[5] The consumptive use and input data are given in graphical form in Figure 4-1.

[6] Represents the change in storage from the beginning to the end of the four-year period.

simplified because it is relatively easy to drain a compartment if needed; and (2) the average depth of water in the storage tank is much deeper, thus reducing the rate of bottom weed growth and the evaporation rate.

In both the single and multiple reservoir storage systems the period during which excess storage is available coincides with summer rains, making salvage of floodwaters a possibility. In this case an auxiliary compartment would need to be constructed to hold floodwater until it could be pumped into the main storage compartment.

b. As indicated earlier the multi-compartmented reservoir has been tested by Cluff [5] at a number of field sites located in the Sahel in Mali, West Africa.

The rainfall in the Sahel varies from 250 to 500 mm [30]. It is received primarily during May through October with approximately 80 percent falling in the months of July and August. The rainfall is highly variable as evidenced by the recent drought in the Sahel in which many people died due to lack of food and water.

Cluff [5] investigated two areas of Mali. The Nara area near Mauritania, west of Mopti, and the Dogen area near Songa, east of Mopti.

The villages in the two regions are lacking in an adequate domestic water supply. In addition, water is needed for irrigation. Although differing in hydrological characteristics both areas contain natural depressions referred to as "mares" in which water collects during the rainy seasons. The mares are rarely deeper than one meter in areas where evaporation loss can exceed two meters per year. Therefore, most of the water is lost to evaporation and the mares always dry up completely during the rainy seasons. The mares are very similar to the playas of the southwestern United States and northern Mexico. The water quality of the mare is, in general, better than that stored in the playas.

Figure 3 depicts the location of mare number 4 within its watershed. This watershed is located near the village of Goumbau about 45 kilometers south of Nara. Cluff [5], using CROP-76, designed a compartmented reservoir system for mare 4 based on rainfall records available from 1921-1965. Coefficients were selected for the water-yield model which gave an average of 38.8 percent of the precipitation appearing as runoff. The low-percentage year was 1963 when only 19.9 percent of the precipitation appeared as runoff, which the maximum being 51.4 percent in 1934. The results of the simulation of compartmented-reservoir system, assuming a 50,000 m^3-collection reservoir from which the water is pumped into the other compartments, are given in Table 1, which shows that over the 45-year period, the system, as designed, would have supplied 346 m^3 of water per week of 1500 m^3 per month and would have been dry only 14 weeks. The overall efficiency of the system is 32.4 percent.

The results of Table 2, are for three depths (2.5, 5.0 and 7.5 meters) and three sets of compartments (1, 3 and 6). The compartments in each set are of equal volume with the total volume of each set equal to 75,000 m^3. The range in depth is selected to be within the constraints of physical reality. Due to the relatively small volume, depths much deeper than 7.5 meters are not justified.

The analysis shows that the evaporation loss is so large that the 2.5-meter deep single-compartmented reservoir is empty 509 weeks, or 21.7 percent of the time, with no beneficial consumptive use. The

Table 2. Summary of the Use of Compartmented Reservoir Systems for Mare 4, Goumbau, Mali--depth versus number of compartments with constant volume[1]

Depth	2.5 Meter			5.0 Meter			7.5 Meter		
Number of Compartments	1	3	6	1	3	6	1	3	6
Consumptive Use:									
Total (tcm)	0.0	0.0	234.0	0.0	643.5	819.0	526.5	936.0	936.0
Weekly (m^3)	-	-	100.0	-	275.0	350.0	225.0	400.0	400.0
Evaporation (tcm)	2638.8	2479.7	2239.4	2409.3	1793.1	1633.0	1868.4	1497.0	1071.0
Overdraft (tcm)	-	-	0.5	-	0.8	2.2	0.2	0.4	0.2
Number of Weeks	(509)	(16)	(5)	-	(3)	(7)	(1)	(1)	(1)
Change in Storage (tcm)	+1.2	+12.5	+10.9	+15.9	+13.1	+11.1	+14.3	+12.0	+11.7
Storage Efficiency (%)[2]	0.0	0.0	9.4	0.0	25.9	33.0	21.2	37.7	38.1
Minimum Storage (tcm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Amount Pumped:									
Concentration (tcm)	0.0	464.1	347.2	0.0	340.0	198.9	169.7	254.6	148.0
Initial (tcm)	-	2506.0	2077.6	0.0	2309.8	2288.6	2293.4	2251.1	2256.5
Excess (tcm)[3]	14.2	21.4	0.0	88.2	45.5	33.3	85.0	49.7	43.4

[1] Total capacity of the reservoir system was kept constant at 75,000 m^3. When three compartments were used, compartments were 25,000 m^3 in size; when six were used, compartments were 12,500 m^3 in size.

[2] Efficiency = 100 (C.U. ± change in storage)/runoff. Total runoff = 2493.9 mcm.

[3] Excess = runoff more than the total available storage of 75,000 m^3.

six-compartmented system supplies up to 100 m^3 per week for the entire period of record except for five weeks; i.e., water would be available 99.8 percent of the time. At a 100-m^3 per week use rate, the storage efficiency of use for a one-compartmented system is still zero whereas for a three-compartmented reservoir the efficiency is 25.9 percent and for a six-compartmented system the efficiency is 33.0 percent. With a 7.5-meter depth, a 21.2-percent utilization can be obtained with a one-compartmented system versus 37.7 and 38.1 percent for three- and six-compartmented systems, respectively. There is not much difference between a three- and six-compartmented reservoir system at this depth. Also there is less pumping required to keep the water concentrated in the six-compartmented system than in the three-compartmented system. The amount of pumping and number of times the pump is required also decreases with increasing depth. Additional analysis also showed no significant difference in efficiency due to modifying the volume and order of compartments for both the three- and six-compartmented system for depths of 5.0 and 7.5 meters. Further, there was not enough improvement in efficiency to justify the added construction and layout costs that different sized compartments would require.

The concept of the compartmented system was applied also to the Nara, Mali, area. Nara, a village of 5,000 persons, is a regional center of local government in northeast Mali near Mauritania. The source of water during the dry season is from limited shallow wells dug in and around a large mare near the village.

The watershed feeding the mare at Nara is shown in Fig. 4. The proposed location of a three-compartmented system also is shown in the figure. The watershed consists primarily of exposed clay loam having a relatively low infiltration rate.

A summary of the use of a three-compartmented reservoir for Nara, Mali, using 45 years of records is shown in Table 3. The table shows both a 50,000 m^3 per month and a 100,000 m^3 per month consumptive use during an average year.

Cluff [5] extended his field studies to include storage for water harvesting agrisystem at San Francisco del Barreal, Coahuilla, Mexico. The San Francisco Ejido is approximately 30 kilometers south of Parras near the southern border of northeastern Mexico. The Ejido covers an area of 24,000 hectares that supports a population of 350 inhabitants. The people have few resources primarily due to the arid nature of their environment. For design purposes the records at nearby Viesca, Coahuilla, were considered representative of the climatic conditions at the San Francisco Ejido although it is a little lower in elevation. Ten years of daily records, 1966-1975, are available. These data include daily precipitation and daily pan evaporation. The annual precipitation ranged from a high of 342 mm in 1968 to a low of 97 mm in 1920. The average is 181 mm.

The water resources are very meager throughout the broad alluvial valley in which San Francisco is located. There is a shallow ground water source (water depth = 30 m) in the alluvial fill beneath the Ejido but is is saline. Tests have shown that the water is unsuitable for agriculture unless it is blended with high quality runoff water. Further supply is limited and can be used only for agriculture during periods of drought.

Soil analysis indicate that the soils are saline-sodic containing about 10 percent clay. The soil contains enough sodium to yield a high percentage of runoff when compacted. The soil under the planted area can be reclaimed if high-quality surface water is used.

Table 3. Summary of Use of Compartmented Reservoir for Nara, Mali--Using 45 years of records, 1921-1965 (Cluff, 1977)

Depth (m)	10	10
Number of Compartments[1]	3	3
Consumptive Use:		
Monthly (m^3)	50,000	100,000
Weekly (m^3)	11,500	22,500
Evaporation (tcm)	21,912.5	20,505.7
Overdraft (tcm)	0	39.4
Number of Weeks	-	(2)
Change in Storage (tcm)	+650.4	+648.2
Storage Efficiency (%)[2]	55.8	72.3
Minimum Storage (tcm)	648.5	0
Amount Concentrated by Pumping (tcm)	2339	2811.3

[1] Total capacity of the reservoir system was kept constant at 1500 tcm. Three compartments were used; compartments were 500 tcm.

[2] Efficiency = 100 (C.U. ± change in storage)/water stored. Total runoff = 151.2 mcm. Runoff in excess of the capacity of the above reservoir system was kept in an existing "mare" which was approximated by a 4,000,000 m^3 reservoir four meters deep. The loss in water from the mare was not included in the determination of the above efficiencies.

The conditions for a water harvesting system seem ideal except for the relatively low precipitation. The relatively low annual precipitation makes the use of a compartmented reservoir essential for optimum water production. As will be discussed in a later section of this report, a small number of mature peach and fig trees now growing in temporal areas provide encouraging evidence that fruit trees can be grown and will survive using water harvesting methods. However, the production from the trees is limited to the years when high precipitation is obtained.

A 20-hectare water harvesting system with a three-compartmented reservoir was designed for the site pictured in Fig. 5. The construction design is shown in Fig. 7.

Using monthly precipitation data from nearby Parras, Coahuilla, simulation of the performance of the system of Fig. 7 is given in Table 4. The design was checked using CROP-76 and the ten years of record available from viesca. The analysis showed that the design was adequate except that the receiving compartment needed to be twice as large in capacity to avoid excessive overflow before the water can be pumped into deeper compartments.

B. WATER HARVESTING USING SUBSURFACE SOIL STRATA

1. Introduction

Water supply using <u>subsurface soil strata</u> as a reservoir supply system consists of several components: infiltration, storage capability of the fallow soil, and evaporation.

Infiltration can be controlled by surface treatment as previously discussed. The storage capability of the selected fallow soil can be determined by standard laboratory procedures. The key to using subsurface soil strata for water harvesting is identification of those

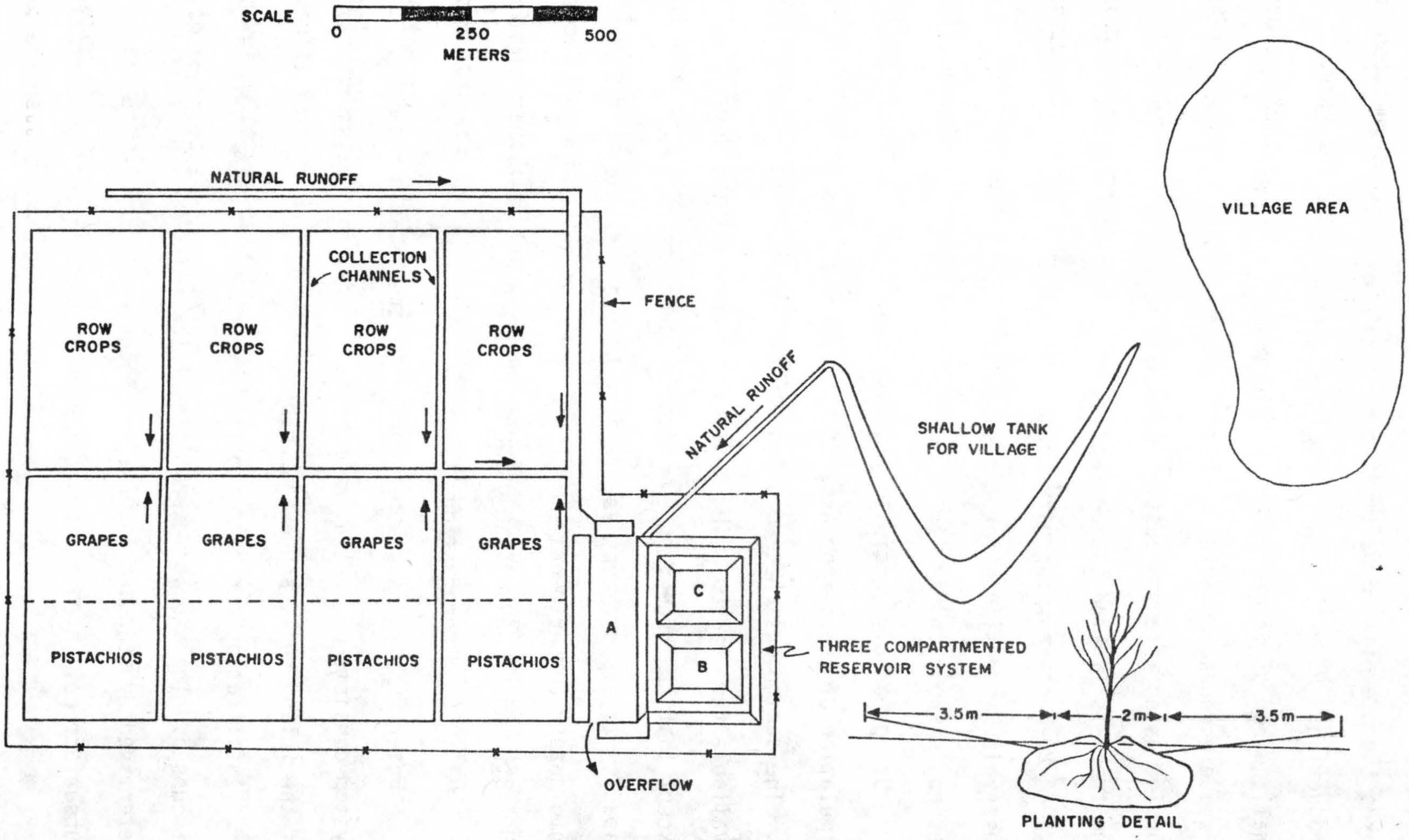


Figure 7. Twenty-Hectare Water-Harvesting Agrisystem and Compartmented Reservoir (Cluff, 1977)

Table 4. Water Budget for San Francisco del Barreal Water Harvesting Agrisystem--from Cluff, 1976

			Runoff (m^3)			Consumptive Use (m^3)		Available Soil Moisture[7] m^3	Surface Storage (m^3)		
Months	Evap. (mm)[1]	Rain (mm)[2]	Treated[3]	Natural[4]	Total	Orchard[5]	Row Crops[6]		Inflow and Discharge[8]	Evap. Loss[9]	Net Volume[10]
Jan.	111	8						11,250		480	28,220
Feb.	127	8				465		10,785		549	27,670
Mar.	196	5				1395		9,390		847	26,825
Apr.	226	6				1800		7,590		976	25,840
May	229	16	720		720	2325		11,250	-5791	989	10,060
June	203	37	3,240	2,400	5,640	2325		14,565			19,060
July	194	48	4,560	4,600	9,160	2325	2700+	15,000	+6400		22,760
Aug.	170	41	3,720	3,200	6,920	1860	2200	15,000	+5060		25,620
Sep.	135	38	3,360	2,600	5,960	1350	1500	15,000	+4610	583	28,150
Oct.	113	20	1,200		1,200	930	1000	15,000	+270	488	26,935
Nov.	94	8				225		14,775		496	26,530
Dec.	105	10						14,775		454	26,070
Totals	1910+	250	16,800	12,800	29,600	15,000	(7400)			5772	
% Runoff			34	5.1							

[1] Pan evaporation at Parras was used after multiplying by a 0.85 pan coefficient insteady of the usual 0.70 to reflect the higher evaporation loss at San Francisco del Barreal.

[2] Average rainfall for Parras, Coahuilla, was reduced by (250/247) to reflect the difference in climatic regimes.

[3] Runoff from treated area = 0.0006 A (R-10) where A = 200,000 m^2 (20 hectares) and R = the monthly rainfall in mm.

[4] Runoff from natural area - 0.002 A (R-25) where A = 1,000,000 m^2 (100 hectares) and R = monthly rainfall in mm.

[5] Consumptive use is based on 6800 liters per tree with 220 trees per Ha. Total annual consumptive use was 15,000 m^3.

[6] Consumptive use is based on 500 mm of supplemental water for the area planted. This planted zone represents 22 percent of the temporal or row crop area.

[7] The available soil moisture is the difference between the field capacity and the permanent wilting point in the soil area within reach of the roots of the trees. The total amount of available soil moisture was 15,000 m^3. The soil moisture was allowed to go down to only 50 percent of capacity of 7500 m^3. At this time the orchard was irrigated to bring the soil moisture back to 75 percent of capacity.

[8] When the soil moisture is at field capacity, excess water goes into the tank. Withdrawals for irrigation is indicated by the negative sign.

[9] Evaporation loss is a function of storage. An evaporation cover is proposed for compartment C. When the volume in storage drops below the volume stored in compartment C, there are no losses. Initial storage assumed was 1/2 of the total capacity of 57,400 m^3. The compartmented tank used in obtaining the data in this table had the following sizes:

$A_A = 4320\ m^2$ $A_B = A_C = 4320\ m^2$

$d_A = 1.9\ m$ $d_B = d_C = 5.7\ m$

$V_A = 8200\ m^3$ $V_B = V_C = 24,600\ m^2$

[10] Net storage remaining in the compartmented tank.

factors affecting evaporation from fallow soils and developing methods of reducing evaporation from the soil surface.

Corey and Kemper [6], as well as others, recognized that mulches had a potential for use either in association with crop culture to retain moisture within the root zone, or as a device to increase infiltration to a ground water aquifer under uncultivated land. In either case, they recognized that the basic problem was to find a way of accomplishing the conservation of precipitation economically.

The first relevant study was reported in a thesis by Schleusener [24], who investigated the effect on evaporation through treatment of fallow soil surfaces. The study included two soil types, a clay loam and a fine sand, and ten different surface treatments for each soil, the most effective treatment was found to be the <u>gravel mulch</u> (Fig. 8).

Corey and Kemper [6] continued the study by Schleusener to determine the kind of gravel mulch that would be most suitable under various soil and atmospheric conditions to control evaporation and increase infiltration. The initial experiments were carried out with relatively short columns containing very wet soil at the time the evaporation measurements were started; therefore, the next phase of study considered the question of the effectiveness of gravel mulches when the soil was initially at field capacity or some lesser moisture content. The experimental results in Fig. 9 show that evaporation from soil columns covered with gravel mulch was essentially independent of the starting water conditions with the soil surface initially being moist in every case.

To simulate field conditions, where soil profiles are ordinarily deeper than the length of columns generally used in laboratory studies and are wetted throughout their depth, Corey and Kemper [6] experimented

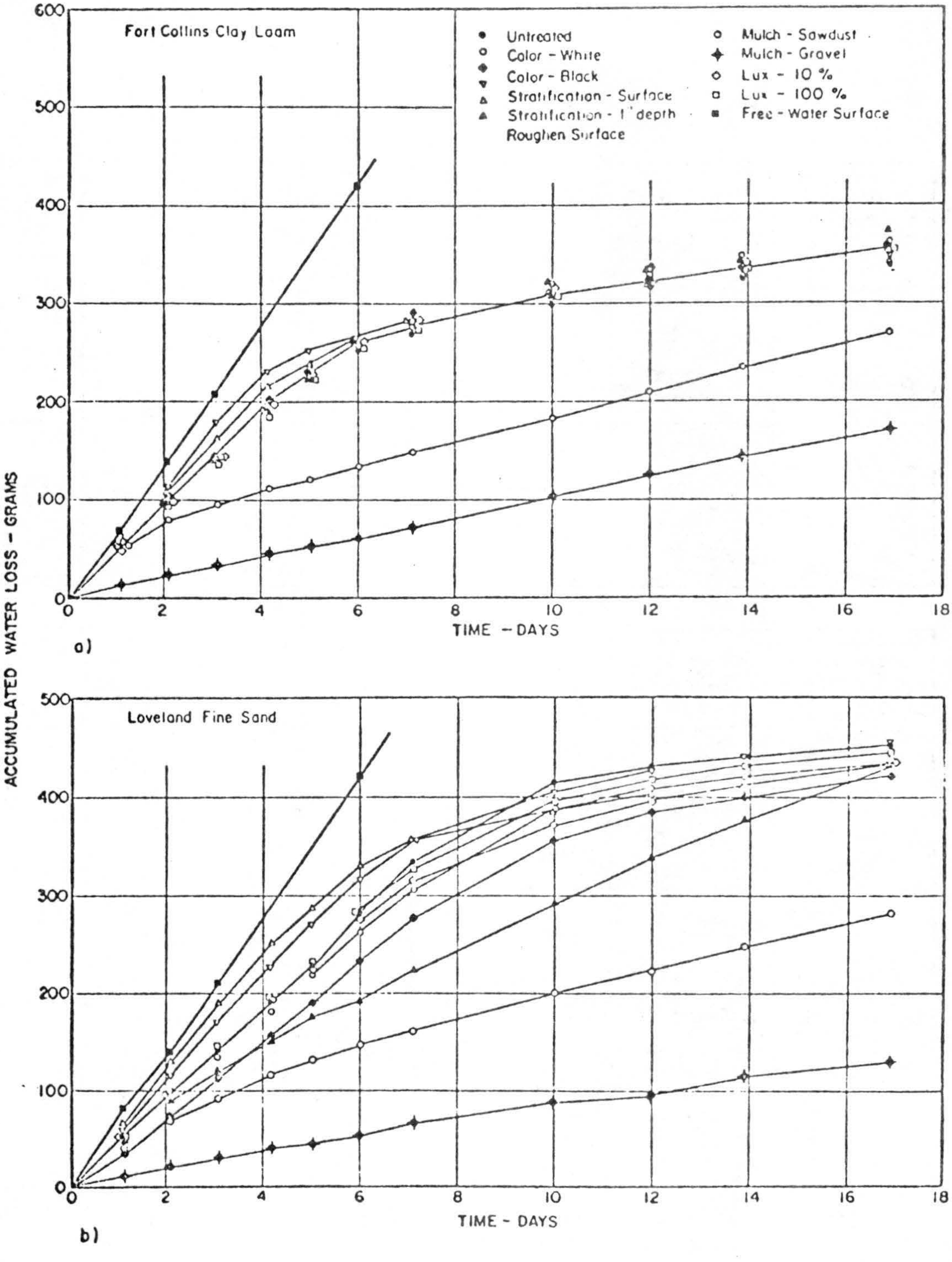


Figure 8. Effect of Surface Treatment on Evaporation from Fallow Soil (Schleusener, 1958)

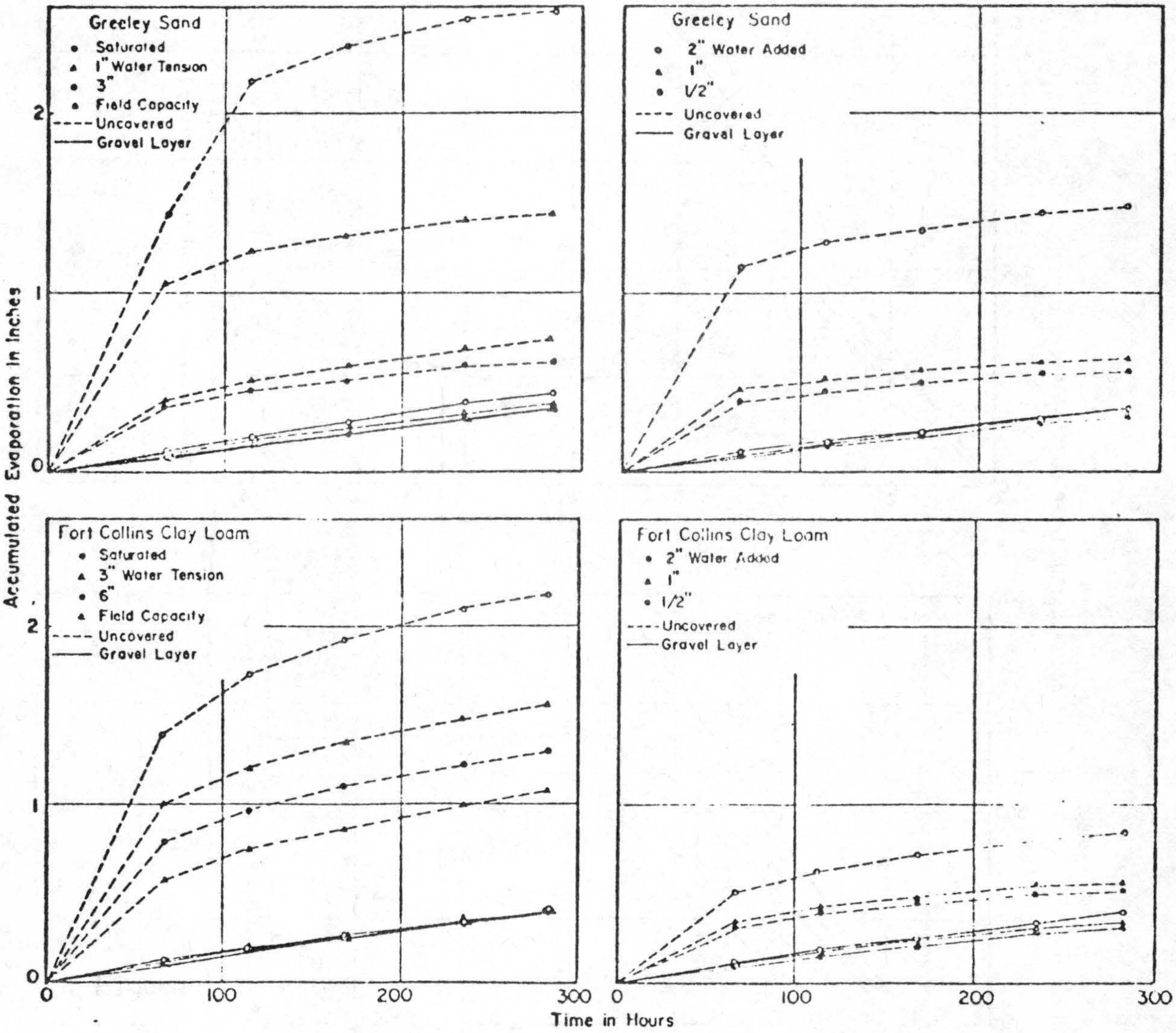


Figure 9. Effect of Initial Soil Water Content on Conservation of Water by a Gravel Mulch (Corey and Kemper, 1968)

with sandy loam columns of various length, and with the initial water content at approximately field capacity. Just enough water was added to each soil sample to permit the water to spread to the bottom of the column in a period of a few days, the amount having been predetermined by trial. Test results clearly indicated that gravel mulches could be used as a method of conserving water from precipitation. They also indicated what is required for a satisfactory mulch and under what rainfall distributions such a mulch is likely to be effective.

To achieve quantitative estimates of the amount of water that could be conserved by mulches under particular field conditions, Corey and Kemper [6] conducted field trials with two objectives: First, to verify the results of laboratory studies regarding the ability of gravel mulch to conserve moisture under field conditions, and secondly, to determine how much of an area at the soil surface surrounding a given point in the soil should be covered with gravel in order to conserve a significant quantity of moisture at that point. Four different gravel treatments were used with particle size ranging from 0.4 to 9 cm in diameter. The four gravels were crushed red sandstone, crushed feldspare, crushed granite material characteristic of river deposites, and grey sand. All treatments were duplicated, and the data presented in Fig. 10 are averages of the duplicates.

In Fig. 10, the amount of precipitation retained by the soil, plus that which passed through the soil, is plotted as a function of time. The differences in amount of water accumulated under the 5 cm gravel mulch, compared to that accumulated under bare soil (6 cm), demonstrated the great potential of such mulches for increasing recharge to ground water aquifers for subsurface soil strata.

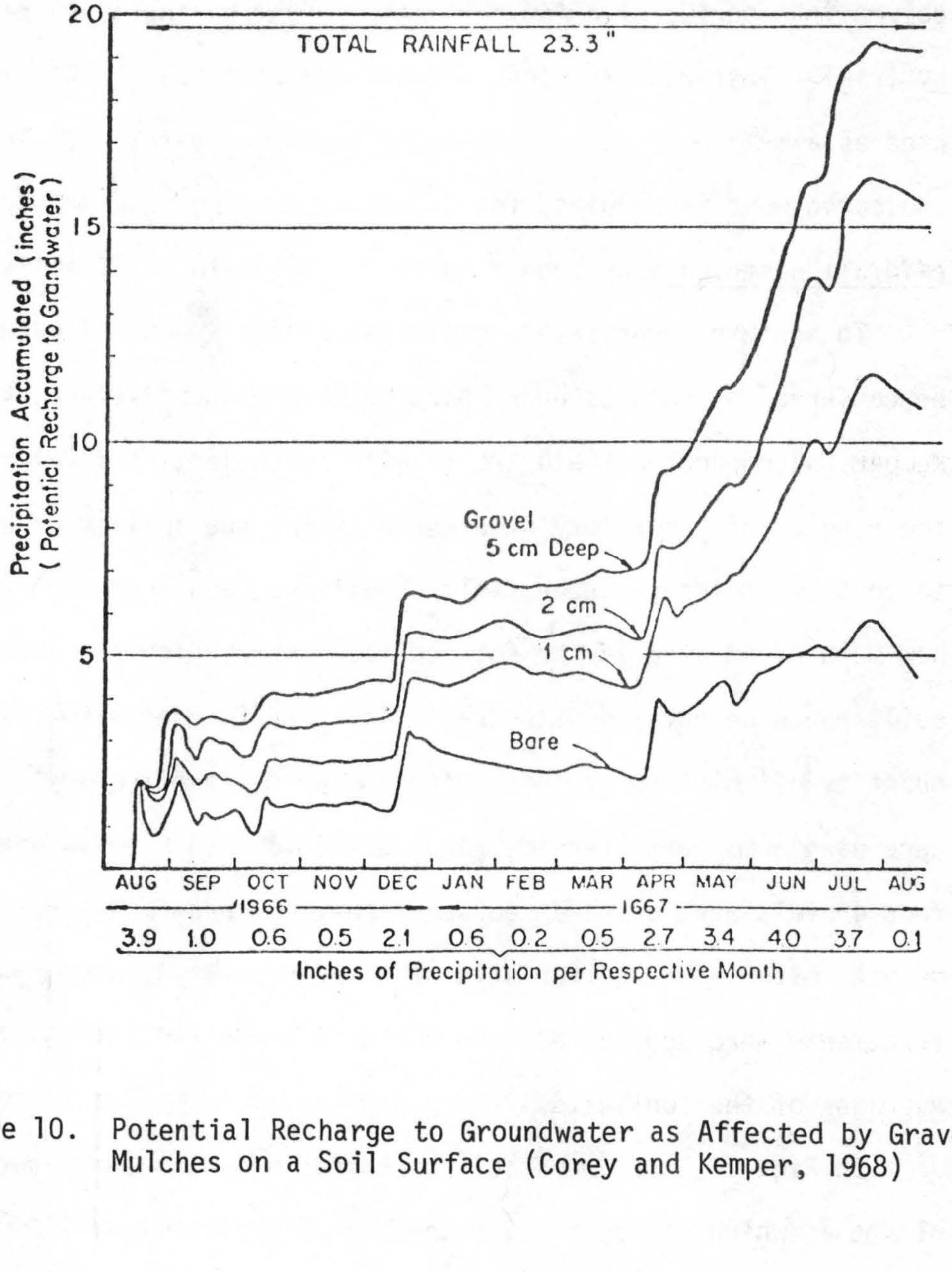


Figure 10. Potential Recharge to Groundwater as Affected by Gravel Mulches on a Soil Surface (Corey and Kemper, 1968)

It has been long recognized that rural development is often hindered in areas where ground water of good quality is not available from springs or domestic wells. This is particularly true of many arid, semiarid and sub-humid regions of the world where capital may be insufficient for distribution systems needed for treated public water. Water of poor quality is often used because its treatment or replacement cost is higher than the rural people can afford. In many areas it is available as a surface water on a seasonal basis only.

In some locations, natural geologic strata are so arranged that they collect, filter and store precipitation and supply good quality water for domestic purposes through natural springs. On the basis of the studies by Corey and Kemper [6], Corey and Smith [7] constructed three field sites to investigate the feasibility of creating artificial strata to provide a similar function.

Initially, three specific objectives were identified:

1. To investigate a three strata filtration and storage system. The bottom stratum in contact with the natural soil would be an impermeable barrier. The next stratum, 3 to 6 feet deep, would consist of fine sand for filtration and storage. The top stratum, 2 to 6 inches deep, would consist of coarse aggregate to allow rapid infiltration, and greatly reduce evaporation of water. The aggregate would also help control the growth of weeds and grass on the rock strata surface.

2. To develop design criteria from physical and computer models developed by personnel of the Colorado State University College of Engineering for predicting rate and duration of outflow as a function of soil grain size and uniformity, layering and packing, angle of incline, and time and distribution of rainfall.

3. To establish field test sites to confirm and/or evaluate the laboratory studies, including entrapment efficiency, barrier durability, utility of native soil materials for constructing the desired strata, the effect of rainfall duration and intensity, and procedures for minimizing costs and maximizing quantity, quality and reliability of water supplied.

Three field sites were identified: the Ramah Navajo Reservation site, and the Santa Clara Reservation site (Fig. 11) located in New Mexico, and the Pine Ridge Reservation (Oglala Sioux Tribe) located in South Dakota (Fig. 12).

2. Ramah Navajo Field Site

The Ramah Navajo Reservation site is located at the extreme southeast corner of the Colorado Plateau, which touches the southwest edge of the Zuni Mountains. The most significant nearby landmark is the El Morro National Monument approximately 7 miles to the northwest.

Geological studies of the area indicate that the Plateau is composed largely of sedimentary rocks mantled by thin alluvial, eolian, and terrace deposits varying in thickness from 10 to 50 feet. The mean elevation for the locale of the site is 6,800 feet with vegetation consisting largely of piñon-juniper and pine grown on large out croppings of sandstone [29].

For this elevation the mean annual precipitation is approximately 12 inches from Table 5 for the nearby station of Fort Wingate, New Mexico, of 7,000 feet elevation. On the basis of local topography, the locale of the Ramah Navajo Field Site is at the extreme southeast end of a group of three small peaks several miles apart known as Loma Medios with an average elevation of 7,300 feet.

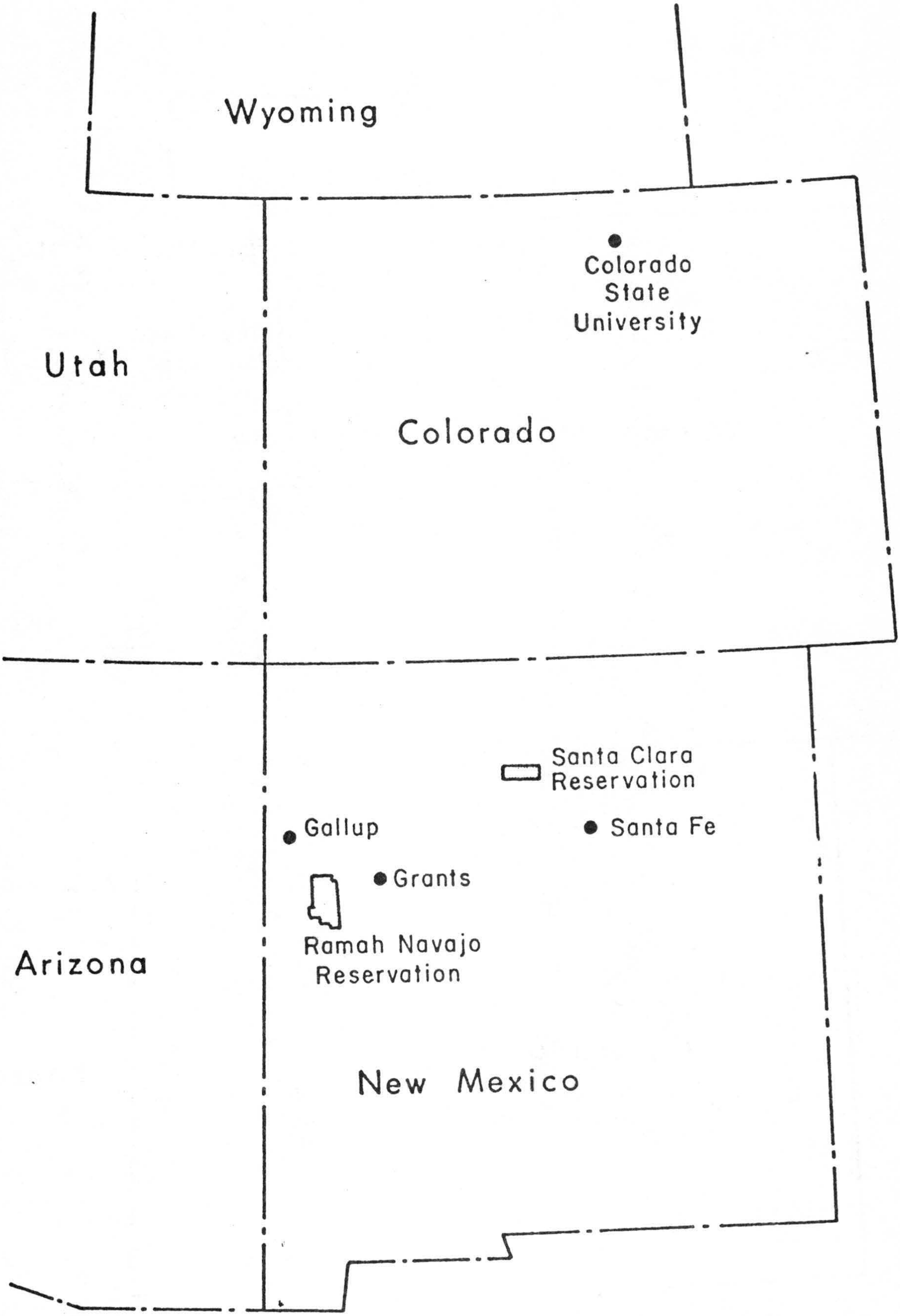


Figure 11. Location of Ramah Navajo Reservation and Santa Clara Reservation (Corey and Smith, 1976)

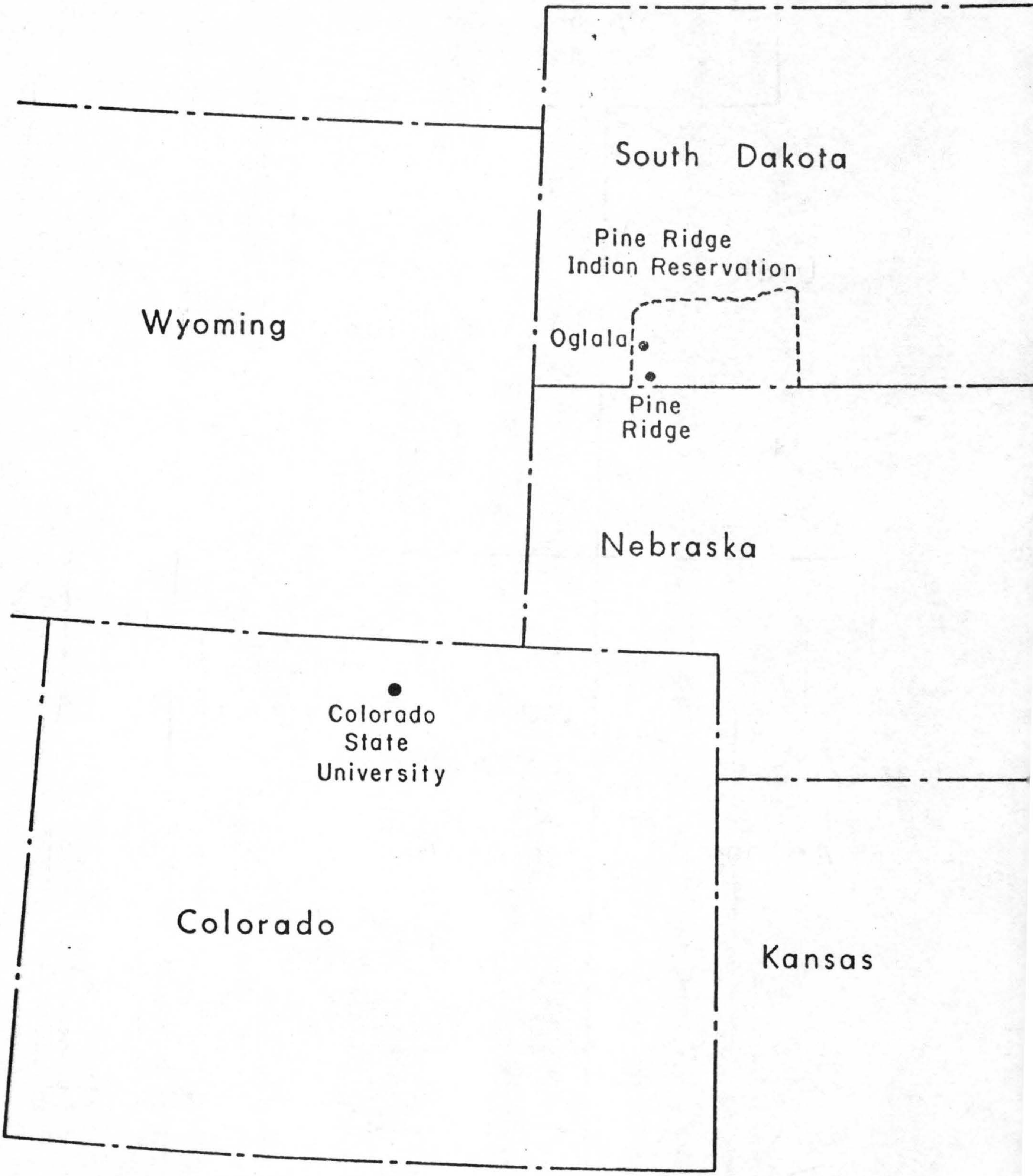


Figure 12. Location of Pine Ridge Reservation (Oglala Sioux Tribe) (Corey and Smith, 1976)

Table 5. Climatic Data for Stations in the Navajo and Hopi Indian Reservations and Adjoining Regions (U.S. Weather Bureau, 1911-57; Sellers, 1960a)

Station	Length of record (years)	Altitude (feet)	Mean annual precipitation (inches)	Mean annual snowfall (inches)	Mean annual temperature (°F)
		ARIZONA			
Betatakin	1939-53	7,200	11.72	51.5	49.8
Chinle	1909-57	6,090	9.16	11.0	51.6
Ganado	1929-53	6,350	11.48	28.9	48.7
Grand Canyon	1904-57	6,965	15.81	61.6	48.7
Holbrook	1893-1957	5,069	8.64	9.9	54.8
Jeddito	1931-53	6,700	9.38	38.5	51.6
Kayenta	1916-57	5,675	8.36	17.3	53.0
Lees Ferry	1917-57	3,141	5.95	3.1	62.2
Leupp	1914-53[1]	4,700	6.37	5.4	54.0
Lukachukai	1914-19 1938-53	6,400	12.70	-------------	-------------
Petrified Forest National Park	1931-57	5,460	9.00	9.9	54.6
Tuba City	1898-1957	4,936	6.72	8.9	55.0
Window Rock	1898-1957	6,750	12.61	30.6	47.6
Winslow	1898-1957	4,880	8.05	10.5	55.0
Wupatki	1939-53	4,908	7.75	5.9	57.3
		NEW MEXICO			
Chaco Canyon National Monument	1933-53[2]	6,125	8.53	18.4	50.7
Crownpoint	1915-57[3]	6,978	10.24	26.1	51.2
Farmington CAA Airport	1942-53	5,494	7.96	----------------	51.6
Fort Wingate	1939-52	7,000	12.41	32.0	49.7
Shiprock 1 E	1928-53[4]	4,974	7.35	9.1	53.3
Tohatchi	1927-53	6,800	10.22	22.4	52.0
		UTAH			
Bluff	1911-57[5]	4,315	7.49	9.9	55.5
Mexican Hat	1931-52	4,250	--------------	--------------	57.5
		COLORADO			
Cortez	1931-57[6]	6,177	13.27	39.0	48.8
Mesa Verde National Park	1922-46 1953-57	6,960	18.42	----------------	50.6

---

[1] Snowfall and temperature 1914-26, 1934-53

[2] Snowfall 1933-57

[3] Snowfall 1915-52; temperature 1931-52

[4] Snowfall 1928-52; temperature 1928-54

[5] Snowfall 1911-52

[6] Snowfall 1931-52

The Navajo reservation and adjoining regions of the Colorado Plateau can be separated into three broad climatic divisions. These have been designated informally as divisions A and B. Division A is leeward of the main orographic barriers, where rain-shadow effects are most pronounced. Division B is intermediate between the two. The Ramah Navajo Reservation is in Division B (Fig. 13).

The annual precipitation graph of the Navajo country usually has two prominent peaks, either for July or August and between December and February. Summer precipitation ranges from 50 to 65 percent of the annual total. In some years, greatest precipitation may occur either in March or April, or in October or November. The two driest months, May and June, generally receive less than 10 percent of the annual precipitation.

Summer precipitation is sporadic and usually occurs during high-energy convectional and frontal-convectional storms. These storms are distributed randomly in the areas having low relief but are concentrated on and along highlands at altitudes above 7,000 feet. Storms are mostly less than 10 miles in diameter, and each probably consists of several cells 1-3 miles in diameter, where rainfall is concentrated more heavily. Because precipitation is relatively intense, some local runoff and flash flooding result.

Winter precipitation results chiefly from frontal activity and generally is distributed evenly. Intensity is usually low and probably contributes substantially to ground-water recharge. Much of the precipitation in the spring and fall is similar to that in the winter, slow drizzle.

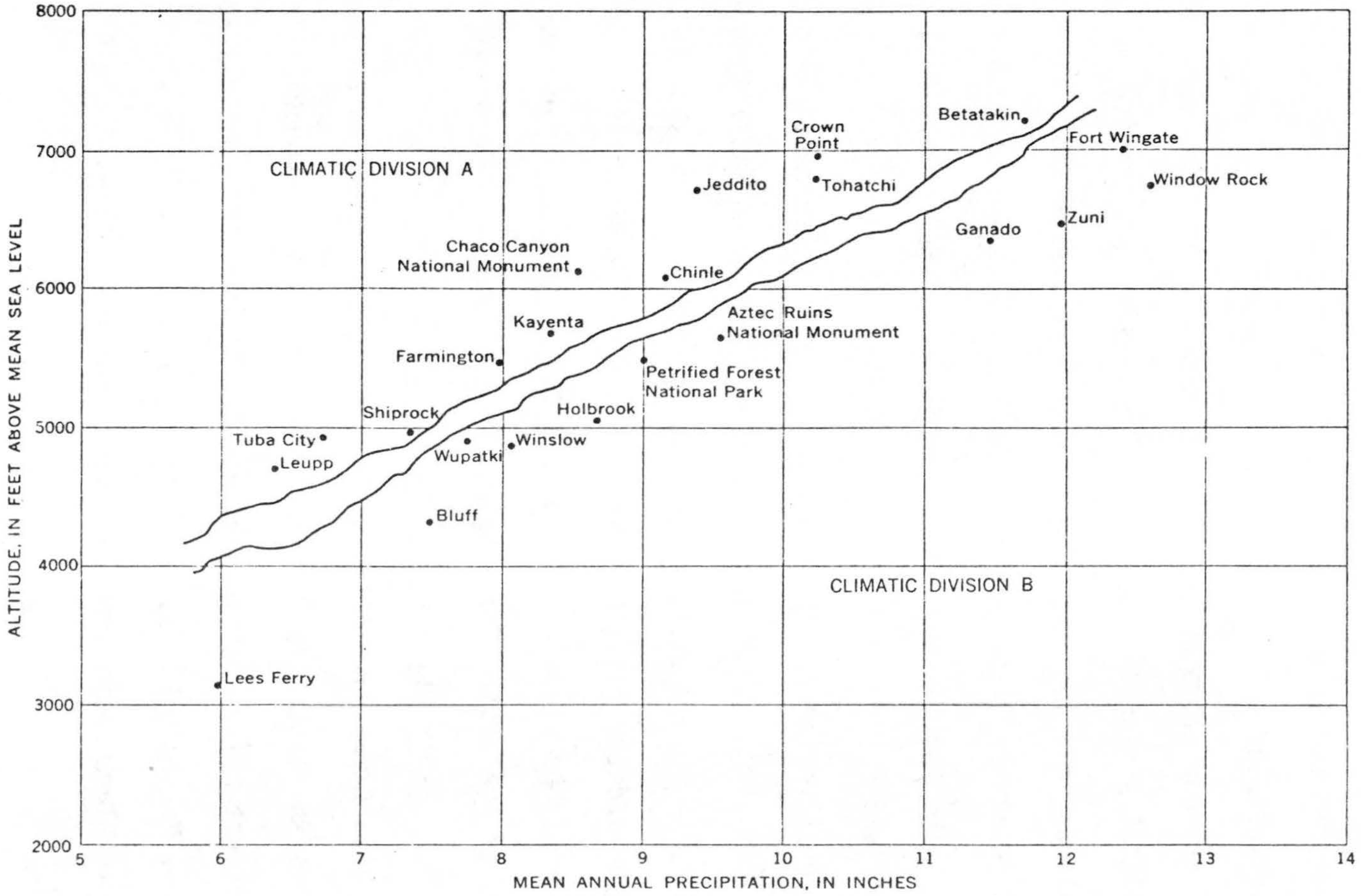


Figure 13. Scatter Diagram of Altitude and Mean Annual Precipitation in the Navajo and Hopi Indian Reservations and Adjoining Regions.

After an extensive field reconnaissance, the Ramah Navajo Field site was located at the base of a sandstone cliff (Fig. 14). The weathered sand located at the base of the cliff was tested and found to be acceptable for use in the construction of the soil and rock strata to trap, filter, and store water for rural domestic use, or, more concisely, an "artificial spring." However, the grain size was considered to be the minimum allowable. The contributing watershed area of approximately 30 acres was relatively flat and with a substantial stand of native grass, which indicated that it would be possible to collect essentially sediment free runoff water.

The construction drawings of Figs. 15 and 16 were typical of all three field sites. The maximum capacity of the Ramah facility was estimated to be 70,000 gallons. A pumping test was made shortly after construction and the results given in Table 6. The quantity of water delivered would be adequate for 15 families of 4 members per family for the period of the test. This assumes 250 gallons per day per family.

3. Santa Clara Pueblo Field Site

The Santa Clara Pueblo field site is located in the Espanola Valley, which enters the east side of the Rio Grande trough, a roughly linear compound structural depression which extends from southern Colorado to southern New Mexico. The specific locale of the site is on a tributary to the Santa Clara Canyon, which drains into the valley of the Rio Grande River [28].

The tributary provides drainage for the Rincon del Cuervo Peak area of the Valles Mountains, which are remnants of a prehistoric volcano. Immediately to the east of the Valles Mountains is the Pajarito Plateau consisting of basalt tuff, which inter-tongues with the Ancha formation.

Figure 14. Strata Site Prior to Construction: Ramah Navajo Reservation (Corey and Smith, 1976)

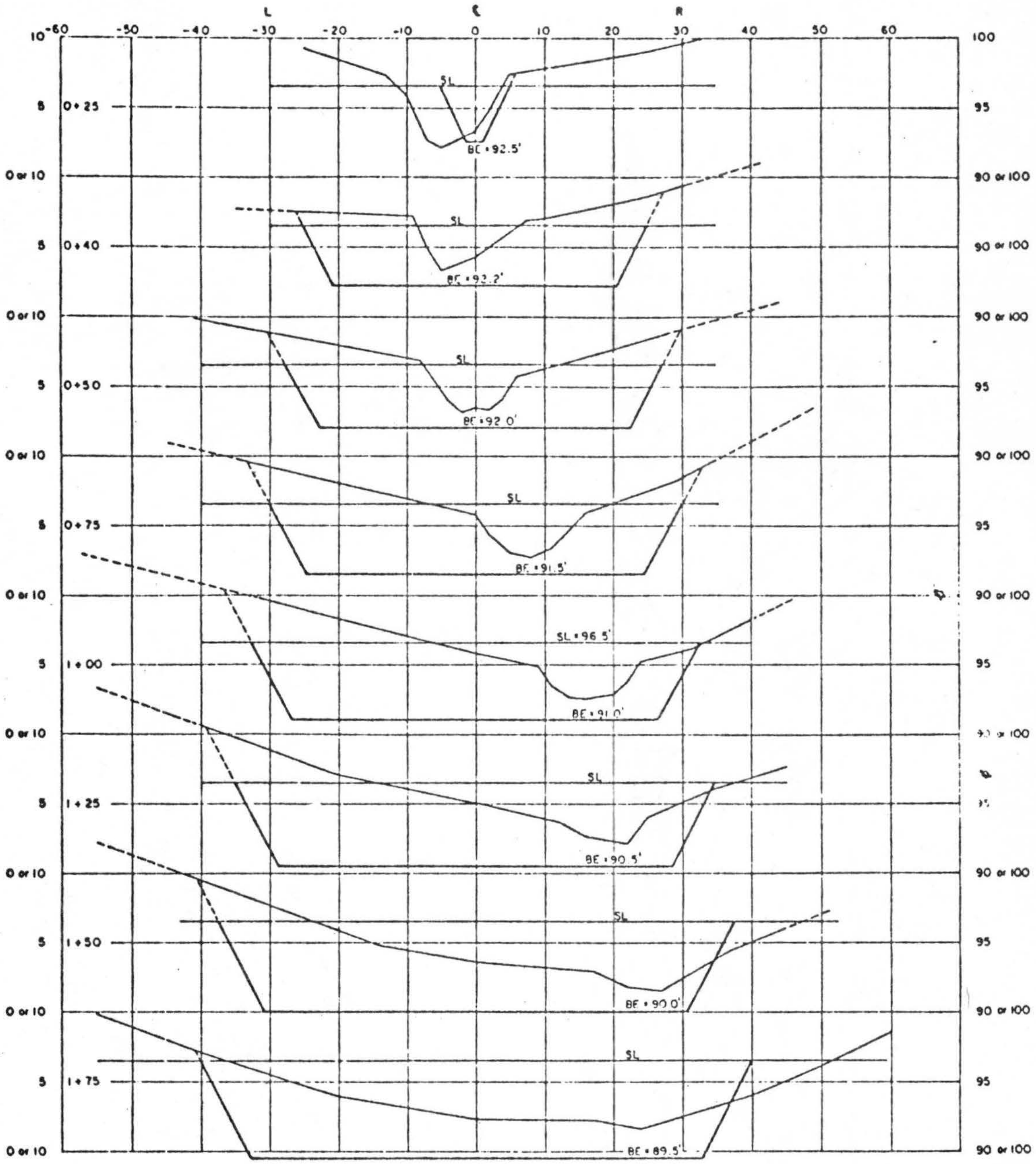


Figure 15. Profile of Strata in the Direction of Runoff Superimposed upon Original Drainage Channel, Ramah Site (Corey and Smith, 1976)

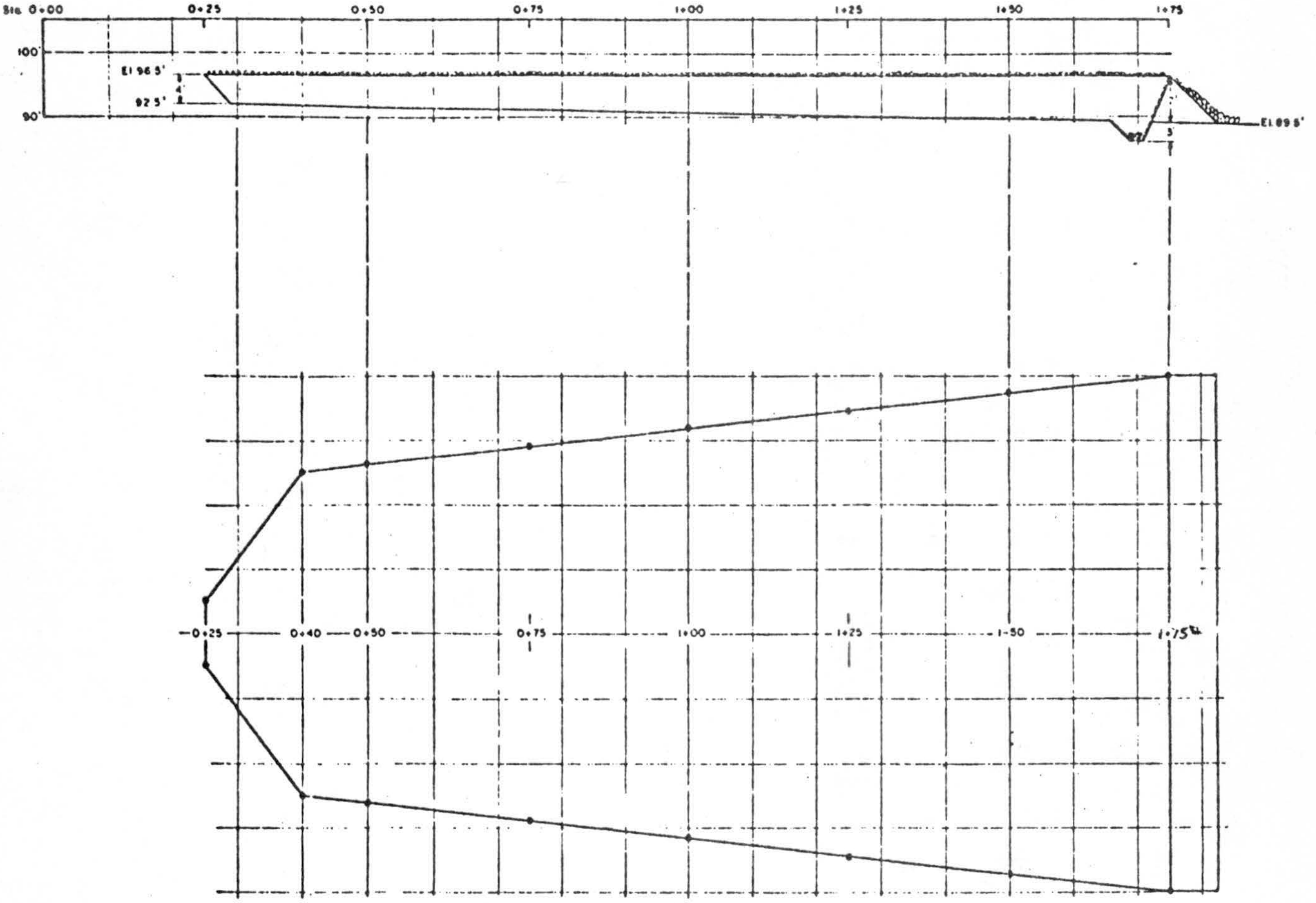


Figure 16. Typical Plan-Profile of Strata for Entrapment, Filtration and Storage of Precipitation for Production of Potable Water, Ramah Site (Corey and Smith, 1976)

Table 6. Pumping Test Ramah Site

Start	Stop	Net Time	q	Total	
Wednesday, May 21, 1975					
6:00	7:00	1 hr @ 3 gpm	180	180	
9:00	10:00	1 hr @ 3 gpm	180	360	
10:50	12:50	2 hr @ 3 gpm	360	720	
1:20	2:20	1 hr @ 3 gpm	180^{check}	900	
2:45	3:45	1 hr @ 3 gpm	180	1080	
6:30	7:30	1 hr @ 3 gpm	180^{check}	1260	1260
Thursday, May 22, 1975					
6:30	8:30	2 hr @ 3 gpm	360^{check}	360	
9:00	11:00	2 hr @ 3 gpm	360	720	
11:30	1:30	2 hr @ 3 gpm	360	1080	
2:00	4:00	2 hr @ 3 gpm	360^{check}	1440	
5:30	7:30	2 hr @ 3 gpm	360	1800	1800
Friday, May 23, 1975					
6:30	8:00	1.5 hr @ 3 gpm	270	270	
9:00	10:30	1.5 hr @ 4 gpm	360	630	630
			TOTAL		3690

Notes: at 10 gpm flow, desaturation (no flow) ≃ 15 minutes
at 6 gpm flow, desaturation (no flow) ≃ 90 minutes
at 3&4 gpm flow, no apparent slowing in two hours

5/23/75 Have been using the water for two days with no ill effects
Good tast, no odor, no color

The Ancha formation in which the experimental site is located consists of gravel and coarse sand, poorly bedded.

In the region of the experimental site of 8,100 feet elevation, two types of storms produce precipitation. During the summer (June-September), the precipitation is produced by frequent thunderstorms, which are in the form of isolated downpours or a series of local showers. From Table 7, for the 8,000-9,000 foot altitude range, the average mean precipitation is 9.3 inches. In the winter (October-May) the precipitation is mostly snowfall, with average mean precipitation of 12.0 inches as indicated in Table 7. The total precipitation of 21.3 inches compares favorably with the nearby Tesuque Creek of Table 8. Total runoff is estimated at 20 percent of the total precipitation or 4.3 inches. Infiltration in summer is high because of absorbent forest soils of gravel and sand and surface mulch; and in winter is negligible due to cold temperatures and frozen ground surface.

The specific locale for the "artificial spring strata" at the Santa Clara Pueblo site in the tributary to the Santa Clara Canyon is shown in Figs. 17 and 18. The strata consisted of clean, river-run sand and coarse-gravel mixture of a maximum diameter of 1/4-inch. The gradation from sand to coarse gravel was fairly uniform. Maximum capacity of the strata was 42,000 gallons with an average discharge of 2 gallons per minute.

4. Oglala Sioux Field Site

The Oglala Sioux Field Site on the Pine Ridge Reservation is located in an area known as Squaw Humper Table. The area is drained by Willow Creek and its tributaries which flow into the White River. The geology of the drainage area is predominantly Pierre shale [9]. There is no significant aquifer within 500 feet of the land surface.

Table 7. Estimates of Average Annual Precipitation on the Upper Santa Fe River Drainage Basin

Altitude (feet)	Area (acres)	Mean precipitation				Volume of water supplied to basin		
		Oct.-May		June-Sept.		Oct.-May	June-Sept.	Total
		(inches)	(feet)	(inches)	(feet)	acre-ft	acre-ft	acre-ft
7,718- 8,000--------	290	9.9	0.82	7.9	0.66	200	200	400
8,000- 9,000--------	4,360	12.0	1.00	9.3	.77	4,400	3,400	7,800
9,000-10,000--------	3,360	16.4	1.37	11.8	.98	4,600	3,300	7,900
10,000-11,000--------	2,200	22.5	1.88	15.1	1.26	4,100	2,800	6,900
11,000-12,409--------	1,450	32.8	2.73	20.0	1.67	4,000	2,400	6,400
Total--------	11,660	--------	--------	--------	--------	17,300	12,100	29,400
Percent--------	--------	--------	--------	--------	--------	59	41	100

Table 8. Annual Average Water Yield of Drainage Basins near Santa Fe, New Mexico

Drainage Basin	Area		Estimated average precipitation	Years record	Annual average water yield[1]				Altitude (feet)		
	(sq mi)	(acres)	(inches)		(acre-ft)	(inches)	Percent of precipitation	acre-ft per sq mi	Minimum in basin	Maximum in basin	Average
Sante Fe River[2]	18.2	11,660	26	38	6,706	6.9	27	370	7,718	12,409	9,700
Tesuque Creek[2]	11.8	7,460	21	14	2,800	4.5	21	238	7,100	12,050	8,750
Little Tesuque Creek[2]	7.2	4,600	19	5	906	2.4	13	126	7,450	11,329	8,700
Arroyo Hondo[2]	6.7	4,290	17	9	535	1.5	9	80	[3]7,250	9,121	[3]8,200
Santa Fe River[4]	8.8	5,620	18	------	680	1.5	8	[5]80	7,348	9,431	8,100
Foothills, Cienega groundwater unit	17.1	15,300	17	------	[6]1,100	[3]1.2	7	[5]64	---------------		[3]7,500
Cienega area, total	137.8	88,000	15	1	[7]4,700	.6	4	34	---------------		[3]6,700
Plains, latitude of Cienega	114	73,000	13	------	3,100	.5	4	27	6,000	7,000	[3]6,500
Plains and badlands, latitude of Sante Fe	282	179,000	13	------	[8]7,050	.5	4	[5]25	5,300	7,500	[3]6,000

[1] Values adjusted to 38-year average discharge of the Santa Fe River

[2] Above present or most recent gaging station

[3] Estimated

[4] Below present gaging station and above Twomile Dam

[5] Exluding Arroyo Hondo

[6] Assumed values

[7] Groundwater discharge only

[8] Excluding contribution of mountain area and direct surface runoff

Figure 17. Strata Locale Prior to Construction. View Looking Upstream of Natural Drainage Channel (Santa Clara Reservation)(Corey and Smith, 1976)

Figure 18. Downstream View of Santa Clara Site (Corey and Smith, 1976)

The Pierre shale is a dark-gray marine shale and mudstone, containing several zones characterized by bentonitic beds. It generally erodes to rolling topography with deeply incised streams. It is not a source of ground water. Very small seeps occur locally in sandy zones, but the water is highly mineralized.

Surface water impounded in small reservoirs or "stock ponds" is commonly used to supply water for cattle, especially in areas of the Reservation generally by either Pierre Shale or the White River Group, both of which consist predominantly of soft shale and clay of low permeability. Because the shale and clay are sufficiently impermeable to prevent significant seepage losses, the greatest loss of water from the stock ponds is by evaporation. Runoff resulting from local thunderstorms, however, is usually enough to make the stock ponds a reliable source of water.

Most precipitation occurs during the late spring and summer, with the largest amounts of falling in May and June. The distribution of runoff is directly related to the distribution of precipitation, except during March when runoff is due primarily to snowmelt.

Flow in Willow Creek and its tributaries is intermittent. During the summer discharges often decrease to only a few cubic feet per second; and during extended dry periods there are many days when no flow occurs.

The specific site selected was in an area where the surface soil rests on a layer of high-swell montmorillonitic clay. Consequently, a membrane as used on the Ramah and Santa Clara sites to prevent leakage was considered unnecessary. Deposits of dune sand were located near the site and this was placed in a small depression to create the artificial aquifer. As in the construction at the Ramah and Santa Clara sites, a dam composed of onsite material sand for the New Mexico sites, and clay for the Pine Ridge site was constructed across the downstream end of the natural or excavated depression (Fig. 19) to retain the water. Also typical of each site a slotted plastic well casing with a gravel envelope was placed at the lower portion of the sand aquifer to collect the water (Fig. 20). A 4-inch diameter outlet pipe was attached at right angles to the slotted pipe for water delivery either to residences, as at the Ramah site, or to stock tanks with float valves as at the Santa Clara and Pine Ridge sites. In all cases the outlet pipe was at a depth sufficient to protect if from frost damage. Similar to the other sites gravel and cobbles were spread over the aquifer sand to a depth of about 6 inches to protect against evaporation and growth of vegetation (Fig. 21). The water capacity of the Pine Ridge site was estimated to be 110,000 gallons.

Recharge to the sand strata will come from occasional runoff and direct precipitation (estimated to be about 12 inches annually although no hydrologic data are available for the area). In order to protect the gravel mulch from collecting sediment, it was considered necessary to maintain a good grass cover on the watershed area above and around the facility. To accomplish this, a wire fence was constructed around the facility enclosing about 10 acres of grass-covered watershed. This was a unique feature to the Pine Ridge site. The purpose of the fence was to protect the grass from grazing and will result in a cover that will protect against erosion during occasional runoff.

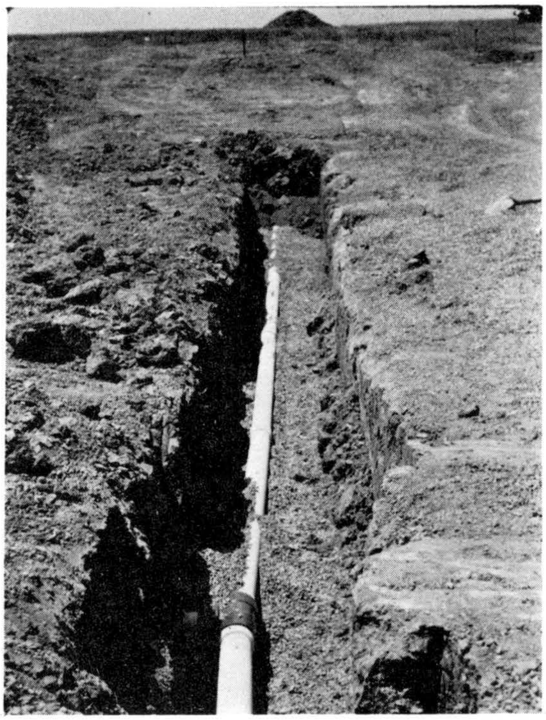


Figure 19. Laying Traverse Perforated Intake Pipe (Pine Ridge Site)(Corey and Smith, 1976)

Figure 20. Construction of Earthen Dike (Pine Ridge Site) (Corey and Smith, 1970)

Figure 21. Laying of Riprap Strata (Pine Ridge Site)
(Corey and Smith, 1976)

II. WATER HARVESTING AND CROP PRODUCTION

A. THE NORTHERN MEXICO PROJECT OF THE DRYLANDS RESEARCH INSTITUTE: UNIVERSITY OF CALIFORNIA

1. Project Area

In July 1967 a cooperative research program was begun between the Drylands Research Institute of the University of California and the Escuela Superior de Agricultura "Antonio Narro" (ESAAN) of the Universidad de Coahuilla, located in Saltillo, Coahuilla [20]. In the initial planning stage several areas were considered for conducting the cooperative research program. Those selected included the lands of the ESAAN near Saltillo, Rancho Los Angeles (which belongs to ESAAN and is located 30 miles south of Saltillo), and Campo Experimental La Sauceda to the north of Saltillo. The characteristics of the three sites are summarized in Table 9 [21].

Table 9. Research Sites in Coahuilla, Mexico

Site	Municipio	Elev. Meters	P_{pt} Mean Annual mm	Temp. Mean Annual °C
Rancho Exp'tl "Los Angeles" of ESAAN	Saltillo	1800	400	14.0
ESAAN at Buena Vista	Saltillo	1700	300	17.7
Campo Exp'tl "La Sauceda"	Ramos Arizpe	1000	250	21.9

The geologic formations of the area are of sedimentary origin, and include limestones, shales, and sandstones of the lower Cretaceous. Some of the limestones are fossiliferous, and others present well-differentiated layering and partial to total weathering. In the layered limestones, some have openings between layers, while others have calcareous cementing materials deposited between layers due to prior passage of water.

The sandstones in the area are of two types, the more common being cemented by calcium carbonate and the other cemented by silicates, often forming a cap on the low ridges. The shales are moderate to high in clay content and generally easily weathered.

The soils derived from the rocks described above are thin residual soils formed under low rainfall conditions and alluvial soils deposited in low-lying areas by runoff waters.

The three sites chosen for initiation of the experimental work were equipped with climate stations to record the principal climatic data. The stations were placed in operation at the beginning of 1968. The instruments installed at each site are listed below.

ESAAN	La Sauceda	Los Angeles
Recording rain gage	Recording rain gage	Recording rain gage
Hygrothermograph	Hygrothermograph	Hygrothermograph
Standard rain gage	Standard rain gage	Standard rain gage
Max-min thermometers	Max-min thermometers	Max-min thermometers
Psychrometer	Psychrometer	Psychrometer
Pyroheliograph	Pyroheliograph	
Pyranometer	Evaporometer	
Evaporation pan	Anemometer (indicating)	
Anemometer (totalizing)		

The data obtained from the climate stations was to be used in interpretation of the results from the various experiments.

2. Research Program

Analysis of the runoff concentration system using contour borders:

In the arid zones which receive their precipitation during the summer, that is, during the crop-growing season, possibilities exist for improving utilization of the irregular rainfall and reliability of crop production by means of runoff water concentration systems which permit the storage of runoff water in the soil to satisfy the consumptive use of various crops.

In the on-site water concentration systems, using contour borders or level bench terraces, an area several meters wide serves as the watershed or runoff area. A second downslope area serves as the crop area where water is retained. The ratio of the two areas and the rainfall-runoff relationship determine the quantity of water made available for crop use. The soil volume of the crop area serves as the storage reservoir for the system. The effective soil volume is limited by the rooting depth of the crop and the characteristics of the soil. For full production, the soil volume must be capable of holding sufficient moisture to meet the evapotranspiration demand between replenishments by rainstorms. Since it is quite unlikely that the conditions for full production can be consistently met (because of the probability distribution of frequency and amounts of rainfall), the ability of the crop varieties to withstand occasional drought is likewise a factor. In summary, the experimental program for concentration of runoff waters for crop production in contour border systems should have the following objectives:

a. Measure on-site runoff and soil moisture in contour border systems with variables of ecologic condition, slope, and watershed area in combination with annual and perennial crops.

b. Determine the proper relation of watershed area to crop area.

c. Determine the relation between site variables and on-site runoff for prediction of runoff in other areas.

The experimental program consisted of 144 experimental plots with three combinations of watershed area and crop area on four representative slopes. The plots were to be used to test production response of corn, fruit trees, and for runoff measurement. The meteorologic, hydrologic, and crop data collected included:

a. Precipitation intensities of the runoff-producing storms from recording rain gages as well as date and depth of rainfall from daily observations of a standard rain gage.

b. Infiltration rates measured for dry and wet soil conditions with a sprinkling-type infiltrometer.

c. Runoff depth produced by the major storms.

The above three items to be used to derive a rainfall-runoff relationship to be used with long-term precipitation data in the analysis.

d. Daily maximum and minimum temperatures to define growing season limits.

e. Daily depth of evapotranspiration measured by a lysimeter, by reduction of soil moisture content, or estimated with coefficients applied to evaporation pan data or by calculations with climatic data.

f. Soil moisture characteristics including field capacity and permanent wilting percentage for calculating the limits of available soil moisture storage.

The design analysis of the contour border system is based on the schematic sketch of Fig. 22 and Equations (1) through (7) as follows:

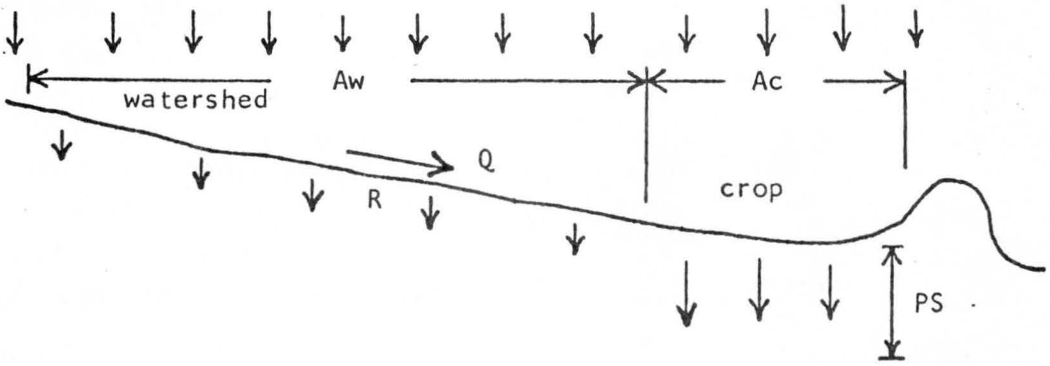


Fig. 22. Schematic Diagram of Contour Border System

A_w = watershed area

A_c = cultivated area

P = storm precipitation, mm

R = storm retention, mm

Q = storm runoff from area A_w, mm

PS = soil depth, mm

HS = soil moisture content, % volume

HS_1 = before,

HS_2 = after, and

HS_3 = between storms

ET = daily evapotranspiration, mm

D = depth of water applied to the area A_c, mm

n = number of days between storms

Thus, from Fig. 22 obtain

$$Q = P-R, \text{ or other relationship} \tag{1}$$

$$D = P + Q \frac{A_w}{A_c} \tag{2}$$

$$\text{Ideally: } D = (HS_2 - HS_1)\, PS \tag{3}$$

$$ET = (HS_2 - HS_3)\ PS \tag{4}$$

$$n = \frac{PS\ (HS_2 - HS_1)}{ET} \tag{5}$$

= limit of days with sufficient water for crop use provided by one storm.

If $D = n\ ET$ and P is an average storm, then from Equation 2 we have

$$D - P = Q\,\frac{A_w}{A_c} \tag{6}$$

and

$$\frac{A_w}{A_c} = \frac{D - P}{Q} = \frac{n\ ET - P}{Q} \tag{7}$$

Giving A_c a value determined by cultural practices, a design value of A_w may be obtained with the P, Q, and ET data. To analyze the system designed with Equation 7, it is necessary to calculate a continuous water balance for a series of years, using various crops with different planting dates and rooting habits.

Taking the initial value of $HS = 0$; after the first rain

$$HS_2 = \frac{D}{PS}$$

and day-by-day

$$HS_3 = HS_2 - n\ ET$$

where $n = 1, 2, 3, \ldots,$ until the second rain before which $HS_3 = HS_1$ and after which

$$HS_2 = HS_1 + \frac{D}{PS}$$

Following the sequence, if HS_3 reaches permanent <u>wilting percentage</u>, ET will be <u>reduced</u> and may be estimated by 0.1 ET until the next rain. During such days of reduced ET, there is danger of permanent damage to the plants and reduction of the yields. Therefore, it is important to tabulate the occurrence, duration, and dates of such days for a series of years and for various values of PS. This tabulation will permit the study of probabilities of successful harvests with various planting dates and different crops.

In cases where HS_2 = field capacity and later HS_3 reaches the wilting percentage due to lack of rain, the situation cannot be improved by increased values of A_w. The value of A_w is also limited by the requirement of providing temporary storage for the runoff water above the borders without border failure during the time required for the water D to infiltrate into area A_c.

3. Research Results

Figures 23, 24 and 25 show the schematic arrangement of the experimental plots constructed at ESAAN. In the figures the following code is used.

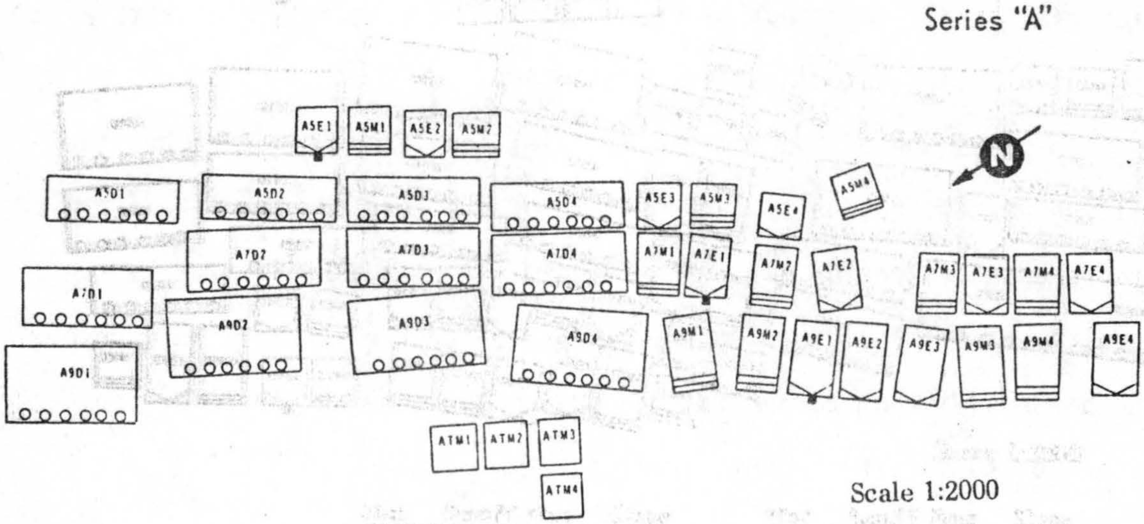
Letter (A,B,C,D) - grouping according to slope

Number (5,7,9) - ratio watershed area to cultivated area

Letter (D,E,M) - crop, D = peach tree, E = runoff measurement from watershed portion, M = corn

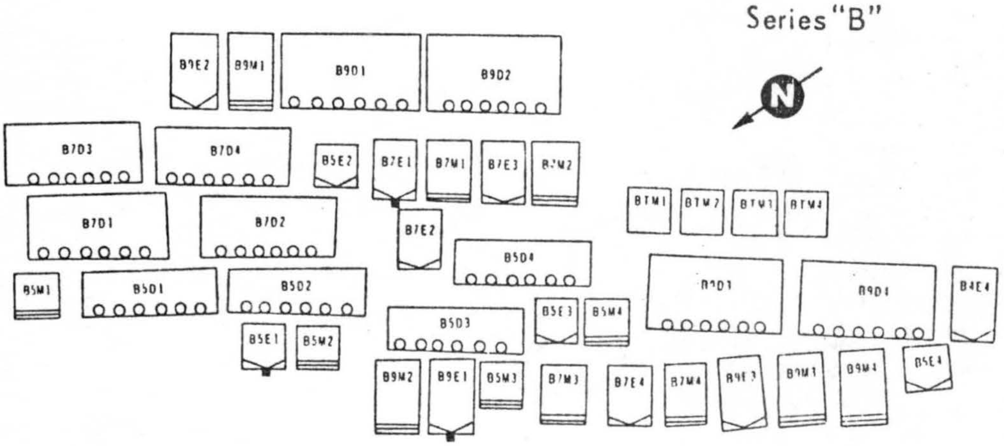
Number (1,2,3,4) - replication of combinations of slope, ratio, and crop

The series A and B plots are located on the upland residual soils on the higher slopes. The textural class for these soils is sandy loam topsoil and silt loam subsoil where subsoil is present. Over most of the area, the topsoil is underlain by layers of calcareous material with variations in its hardness and degree of cementation. The soil surface is covered by considerable gravel and rock fragments. A light to



Plot	Runoff Area	Slope
A5D1	361.0 mt^2	6.9%
A5D2	360.0	6.1
A5D3	360.0	5.2
A5D4	360.0	8.1
A5E1	122.2	5.9
A5E2	60.0	6.0
A5E3	59.0	6.2
A5E4	59.0	4.4
A5M1	120.8	5.6
A5M2	120.0	6.4
A5M3	120.3	8.8
A5M4	120.0	6.3
A7D1	504.4	5.7
A7D2	504.0	6.1
A7D3	504.2	6.9
A7D4	504.0	7.0
A7E1	163.8	7.0
A7E2	84.0	6.8
A7E3	84.0 mt^2	5.0%
A7E4	84.0	3.8
A7M1	168.0	7.6
A7M2	168.0	7.6
A7M3	168.1	6.8
A7M4	168.2	4.2
A9D1	648.2	5.4
A9D2	648.1	5.6
A9D3	648.3	6.8
A9D4	648.0	5.5
A9E1	210.8	5.2
A9E2	106.0	4.3
A9E3	101.0	3.9
A9E4	111.0	7.1
A9M1	216.0	6.3
A9M2	216.0	6.8
A9M3	216.2	4.9
AM4	216.0	6.8

Figure 23. Schematic Arrangement of Experimental Plot: ESAAN Series "C" and "D" (Lewis, 1969)



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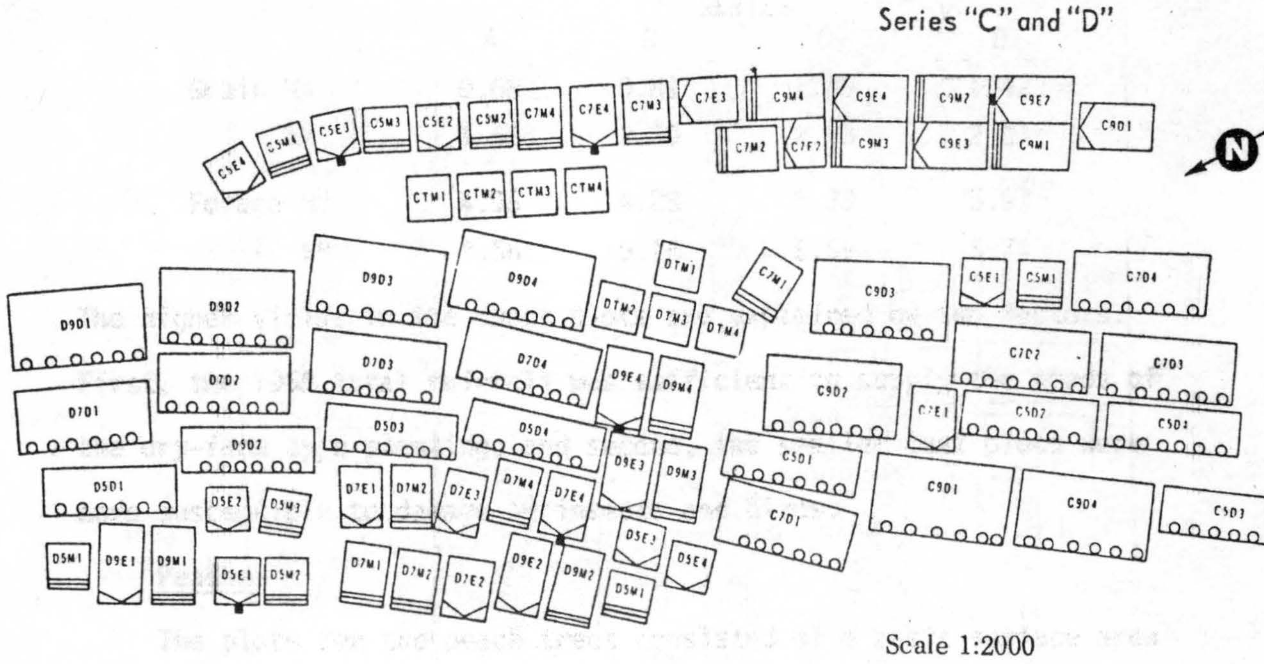
Plot	Runoff Area	Slope	Plot	Runoff Area	Slope
B5D1	361.0 mt^2	4.7%	B7E3	80.0 mt^2	4.1%
B5D2	360.2	5.9	B7E4	82.2	4.5
B5D3	360.0	4.7	B7M1	168.3	5.0
B5D4	360.2	4.7	B7M2	168.0	4.7
B5E1	112.8	4.8	B7M3	168.0	5.5
B5E2	60.0	4.8	B7M4	168.2	4.1
B5E3	61.0	5.1	B9D1	648.0	5.0
B5E4	54.0	3.4	B9D2	648.0	4.8
B5M1	120.2	4.3	B9D3	648.0	5.0
B5M2	120.3	4.4	B9D4	648.0	4.6
B5M3	121.0	5.0	B9E1	207.4	5.5
B5M4	121.0	4.6	B9E2	106.0	4.3
B7D1	504.0	5.5	B9E3	109.2	4.5
B7D2	504.0	5.2	B9E4	104.0	4.1
B7D3	504.1	6.3	B9M1	216.0	5.2
B7D4	504.1	5.5	B9M2	216.0	4.6
B7E1	164.7	5.1	B9M3	216.0	4.8
B7E2	86.0	4.7	B9M4	216.0	4.2

Figure 24. Schematic Arrangement of Experimental Plot: ESAAN Series "B" (Lewis, 1969)



Plot	Runoff Area	Slope	Plot	Runoff Area	Slope
C5D1	361.2 mt^2	6.0%	D5D1	360.2 mt^2	5.3%
C5D2	361.3	4.8	D5D2	360.0	8.0
C5D3	360.0	4.4	D5D3	360.0	4.0
C5D4	360.5	4.6	D5D4	361.0	5.8
C5E1	60.0	3.3	D5E1	112.5	2.9
C5E2	60.0	0.4	D5E2	60.0	5.1
C5E3	105.6	2.2	D5E3	60.0	4.2
C5E4	60.0	1.4	D5E4	60.0	5.1
C5M1	120.0	4.2	D5M1	120.3	5.3
C5M2	121.0	1.9	D5M2	120.2	4.0
C5M3	120.3	3.9	D5M3	120.0	5.5
C5M4	120.0	2.3	D5M4	120.0	5.3
C7D1	504.2	5.2	D7D1	504.0	6.2
C7D2	504.1	4.5	D7D2	504.0	5.4
C7D3	504.0	2.3	D7D3	504.9	4.9
C7D4	504.0	2.2	D7D4	504.0	4.9
C7E1	85.0	3.8	D7E1	83.5	5.6
C7E2	84.0	0.64	D7E2	81.0	5.5
C7E3	84.0	0.42	D7E3	82.0	4.3
C7E4	171.3	1.85	D7E4	165.0	5.3
C7M1	168.2	3.2	D7M1	168.3	4.6
C7M2	168.0	0.64	D7M2	167.2	3.5
C7M3	168.0	1.2	D7M3	168.0	4.8
C7M4	168.0	1.92	D7M4	168.7	4.9
C9D1	648.0	5.4	D9D1	647.8	5.6
C9D2	648.5	4.1	D9D2	648.2	4.2
C9D3	647.9	3.5	D9D3	648.3	4.2
C9D4	648.0	3.5	D9D4	648.0	4.0
C9E1	110.0	2.1	D9E1	107.0	4.7
C9E2	225.0	1.6	D9E2	111.0	3.8
C9E3	110.0	0.44	D9E3	107.0	4.2
C9E4	107.0	1.0	D9E4	229.5	4.1
C9M1	216.0	1.5	D9M1	216.3	4.3
C9M2	216.3	0.61	D9M2	216.0	4.6
C9M3	216.4	0.61	D9M3	216.0	5.5
C9M4	216.4	0.61	D9M4	216.0	4.3

Figure 25. Schematic Arrangement of Experimental Plot: ESAAN Series "C" and "D" (Lewis, 1969)

medium cover of brush plants was removed from the watershed portion of the plots to obtain a uniform cover type of native grasses varying only in cover density.

The series C and D plots are located on the weathered terrace soils which have sandy topsoil underlain by sandy loam subsoil. The area was previously in contour cultivation for small grain, thus the cover of native grasses was sparse, and only a few small rocks were found on the surface.

The contour borders of the crop plots were 30-40 centimeters high, with a 1- to 1-1/2-meter base width. The borders were constructed by moving soil uphill from the downhill side with a plow. The upper and side borders delimiting the contributing area of each plot were 15-cm soil borders constructed by hand.

Corn

The M4 plots and the four TM plots of each series were planted with hybrid corn for evaluation of the corn response to water concentration. The M4 plots consisted of a 2-meter by 12-meter cultivated area below a contributing area, and were planted with two rows of corn one meter apart--with one plant every 30 cm in the rows. The TM plots were 12 by 12 meters, with no contributing area, and were contour planted with the same row and plant spacings to represent a dry-farming check plot. The seedbeds were prepared and given preplant fertilizer in late May, and the plots were seeded on June 16, following 38 mm of rain on June 12 and 13. The plots were hand cultivated periodically for weed control. The corn in the series C and D plots developed chlorosis, which was controlled by foliar application of 1.3 percent iron sulfate solution. The grain and forage were harvested at the end of October. The averaged yields in kg from 26 plants were:

		SERIES			
		A	B	C	D
Grain	M4	0.68	0.81	1.83	1.42
	TM	1.66	2.39	2.03	2.01
Forage	M4	4.96	4.28	5.38	5.91
	TM	4.56	6.16	5.69	5.74

The higher yields in the check plots are explained by two factors. First, the 1968 total rainfall was sufficient to supply the needs of the dry-farm type planting, and second, the smaller test plots were more susceptible to damage by insects and birds.

Peaches

The plots for the peach trees consisted of a basic surface area for each tree 2 meters wide and 6 meters along the contour. Each plot had 6 trees for a total length of 36 meters. After construction of the contour borders, excavations of one cubic meter were made on the uphill side of the border at six-meter intervals. The excavations were refilled halfway with topsoil, which was given a preplant irrigation at the end of March 1968. The first week of April the young trees were planted by filling the excavations to a few centimeters below ground level and adding water at the time of planting. After planting, a rock mulch covering was placed around the tree to prevent bare soil evaporation. The trees were given an additional irrigation two weeks after planting, and then became dependent upon the on-site runoff.

Small auxiliary borders which formed an inverted "V" uphill from the space between the small tree planting basins were installed to insure the concentration of small quantities of runoff at the trees.

The peach trees were of the variety Sun Crest. In June, the trees developed chlorosis, which was corrected by application of 5 grams of iron chelate, dissolved in water, to the soil around each tree. The application was made on July 4. The trees in the C and D series plots became chlorotic again in late August, and were given another 5-gram treatment on September 15.

Measurements of trunk diameter at 30 cm above ground and over-all height were made on June 26 and September 17. The growth data are presented in Table 10. There were no differences in the observed growth due to the different sizes of watershed area.

III. OPTIMIZATION OF WATER HARVESTING SYSTEMS

A. PROBLEM DEFINITION

1. Introduction

The empirical evaluation of water harvesting systems is a lengthy procedure and an expensive one. For the purpose of deciding on optimal dimensions of the system, it would be desirable to formulate a simulation model to investigate the system in a short time and in an inexpensive way. Asfur [1] sought to formulate a simulation model for water harvesting systems and its relation to use in optimization of dryland agriculture. The model considered soil-water-plant relationships, simulation of equally likely rainfall and evapotranspiration sequences and crop response functions to water deficiencies.

His objective was to devise a technique whereby decisions on the optimal dimensions of the water harvesting systems may be attained. He did not attempt to find a solution for a specific problem, but rather to illustrate the use and performance of the different components--precipitation, soil moisture content, soil type, etc.--by a case study.

Table 10. Peach Tree Growth Data (averages of 24 trees) (Lewis, 1969)

	Height		Amount of Growth	Trunk Diameter		Amount of Growth
	6-26	9-17		6-26	9-17	
	cm	cm	cm	cm	cm	cm
A5	101	123	22	1.38	2.18	0.80
A7	95	124	29	1.38	2.24	0.86
A9	98	122	24	1.49	2.48	1.01
B5	98	114	16	1.43	2.31	0.88
B7	99	117	18	1.40	2.27	0.87
B9	95	119	24	1.38	2.26	0.88
C5	86	108	22	1.31	1.98	0.67
C7	89	102	13	1.26	1.94	0.68
C9	85	100	15	1.27	1.86	0.59
D5	91	118	27	1.32	2.29	0.97
D7	90	98	8	1.33	2.04	0.71
D9	92	116	24	1.37	2.14	0.77

2. *Methodology*

Asfar [1] made use of *simualtion*, which has been defined as reproducing the essence of a system without reproducing the system itself. The essential characteristics of the system are reproduced in a model which is then studied in an abbreviated time scale. The resulting model can be a *physical representation* of the system which is formulated and constructed with dimensional and time scales, but adhering to the laws of dimensional similitude. However, the prevalent usage of the term simulation has come to mean a model which is formulated by using arithmetic and algebraic relationships along with nonmathematical logical processes. This type of model is not intended to be solved algebraically, but rather by *simulation of real systems* using a digital, analog- or hybrid-computer system.

a. *The Water Balance Model*--Asfur [1] using the studies by Lewis [21] analyzes the *water balance model* exemplified by the *on-site concentration systems* using contour borders or level bench terraces of Fig. 26 (see Fig. 22) for crop production in arid or semiarid regions of the world.

In the *on-site concentration system* an area serves as the watershed or runoff area, whcih is referred to as the *harvesting area*. A second downslope area may serve as the *crop area* where water is retained. The *root zone* under this area is the *reservoir* for the system. The horizontal width of the harvesting area is referred to by y, and x is the corresponding width for the crop area. The *ratio* y/x, all other things being equal, determines the quantity of water concentrated for crop use. The soil volume of the crop area serves as the storage reservoir of the system. The *effective soil volume* is limited by the

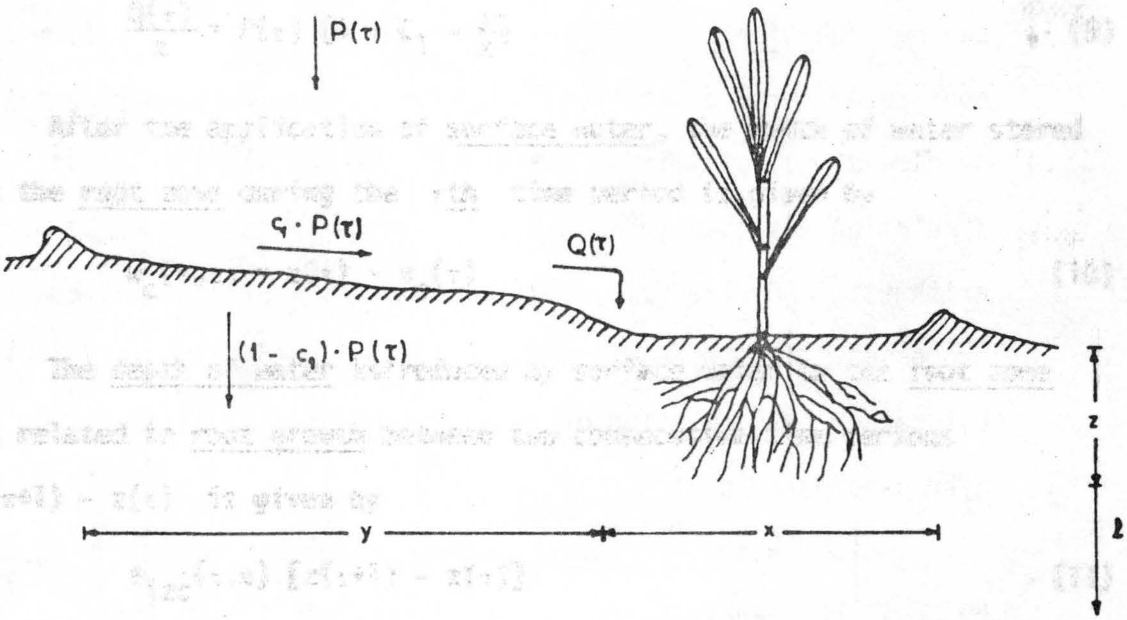


Figure 26. The Physical Model of the Water Harvesting System of the Study. $P(\tau)$ is depth of rainfall during the τth time period, c_1 is the coefficient of runoff and $Q(\tau)$ is the volume of runoff per unit length. y and x are the widths of the water harvesting and crop areas respectively. z is the depth of effective root zone. ℓ is a distance measured from end of root zone (Asfur, 1972)

crop's effective root zone, z. For full production, this soil volume must be capable of holding sufficient moisture to meet the evapotranspiration demand between replenishments by rainfall. The objective is to find an optimal y/x ratio that most likely would result in crop yield greater than a certain quantity most of the time. The risk and reliability of the system is introduced because of the probability distribution of frequency and amounts of rainfall. Hence, it is quite unlikely that the conditions for full production can be met. It is assumed that there is no lateral water movement in the soil profile and there are no problems of salinity and/or fertility. Moreover, it is assumed that the soil moisture in the effective root zone is equally available to the plant regardless of specific locality of the moisture in the root zone.

In Fig. 26, Asfur [1] defines the following terms:

$P(\tau)$ = precipitation during the τth time period.

C_1 = runoff coefficient ($0 \leq C_1 \leq 1$) dependent on soil moisture content, soil type, slope, intensity and duration of rainfall.

$Q(\tau)$ = volume of runoff from the harvesting area (y) per unit length due to rainfall during the τth time period.

In addition to the above, Asfur [1] defines the following:

θ_c = the volumetric moisture content in the root zone of the cropped area.

$\theta_{izc}(\tau,\ell)$ = initial volumetric moisture content in the soil below the root zone as a function of the distance, ℓ, and time period, τ.

$ET_p(\tau)$ = potential evapotranspiration during τth time period.

$ET_a(\tau)$ = actual evapotranspiration during τth time period.

In his theoretical analysis Asfur [1] relates runoff to depth of water applied to cropped area by

$$\frac{Q(\tau)}{x} = C_1 \cdot P(\tau) \cdot \frac{y}{x} \tag{8}$$

and the total depth of water received by the cropped area during the τth time period by

$$\frac{Q(\tau)}{x} = P(\tau) \left[1 + C_1 \cdot \frac{y}{x}\right] \tag{9}$$

After the application of surface water, the depth of water stored in the root zone during the τth time period is given by

$$w_c(\tau,z) = z(\tau) \cdot \theta_c(\tau) \tag{10}$$

The depth of water introduced by surface water to the root zone as related to root growth between two consecutive time periods $z(\tau+1) - z(\tau)$ is given by

$$\theta_{izc}(\tau,\ell) \left[z(\tau+1) - z(\tau)\right] \tag{11}$$

The water balance between the applied surface water and water stored in the root zone at the beginning of the τ + 1st period is given by

$$w_c(\tau+1,z) = w_c(\tau,z) + P(\tau)\left[1+C_1 \cdot \frac{y}{x}\right] + \theta_{izc}(\tau,\ell)\left[z(\tau+1)-z(\tau)\right] - ET_a(\tau) \tag{12}$$

where

$$ET_a(\tau) = C_2 \cdot ET_p(\tau) \tag{13}$$

and C_2 is a coefficient dependent on crop, soil type, soil moisture content, etc.

If the depth of water at field capacity is $w_{FC}(z)$, then the water stored in the root zone $w_c(\tau+1,z)$ could be less than, equal to, or greater than $w_{FC}(z)$. Deep percolation would occur in the latter case, and Equation 12 would be redefined by

$$w_c(\tau+1,z) = \min\{w_{FC}(z),\ w_c(\tau,z) + P(\tau)[1+C_1 \cdot \frac{y}{x}] + \theta_{izc}(\tau,\ell)[z(\tau+1)-z(\tau)] - ET_a(\tau)\} \qquad (14)$$

For deep percolation, the drainage water is assumed to increase the soil moisture content in the soil immediately below the current effective root zone to field capacity. For this condition, Asfur [1] divided the soil moisture content into depth of drainage water by $dw_c(\tau)$. For these two variables he gives the following respective relations:

$$dw_c(\tau) = \{w_c(\tau,z) + P(\tau)[1+C_1 \frac{y}{x}] + \theta_{izc}(\tau,\ell)[z(\tau+1) - z(\tau)] - ET_a(\tau)\} - w_{FC}(z) \qquad (15)$$

and

$$dz_c(\tau) = dw_c(\tau)/(\theta_{FC} - \theta_{izc}) \qquad (16)$$

Water loss in the root zone by evapotranspiration would result in an upward gradient; however, such gradient was assumed to be small and hence neglected by Asfur [1].

For water depth in the soil at the $\tau + 1$st time period as a function of infiltration of rainfall water (input) and evaporation (output), Asfur [1] gives the expression

$$w_H(\tau+1,z) = w_H(\tau,z) + (1 - C_1)\ P(\tau) - EV(\tau) \qquad (17)$$

where $w_H(\tau,z) = z(\tau)$ is depth of water stored in a depth equivalent to the root zone of the crop in the adjacent area at the τth time period, and $\theta_H(\tau)$ is the volumetric moisture content in the harvesting area at the τth time period. The water depth at the $\tau + 1$st time period might be less than, equal to, or greater than the depth of water at field capacity. The latter case results in drainage water given by

$$dw_H(\tau) = w_H(\tau,z) + (1-C_1)\ P(\tau) - EV(\tau) - w_{FC}(z) \tag{18}$$

The depth of soil that is brought to field capacity is given by

$$dz_H(\tau) = dw_H(\tau)/(\theta_{FC} - \theta_{izH}) \tag{19}$$

From the above analysis and the resulting relationships, Asfur [1] noted that it would be possible to maintain a record of the simulated soil moisture regime over the entire length of the time under consideration provided amounts and times of rainfall can be simulated. Rainfall simulation poses no problem since it can be generated through a mathematical model that possesses all the statistical characteristics of the historic record from which it is developed. The basic problem is how to relate the soil moisture regime to the yield of the crop under consideration. Because of the lack of experimental data to evaluate these functions, Asfur [1] resorted to the use of crop response functions in his analysis.

Crop Response Functions

The crop yield is dependent on the soil moisture regime at the different stages of growth. In general, the relative rate of plant growth is a function of the mean soil moisture stress in the active root zone; that is, plant growth is related to the matric suction caused by the retentive forces that hold the water in the soil. Many soil, plant, and environmental factors are known to affect the dynamic processes of water in the soil-plant-atmosphere continuum. The seasonal pattern of water use by a crop is of significance in relation to the probability of developing stress. This water use consists of both soil evaporation and plant transpiration, commonly referred to by evapotranspiration. Evapotranspiration interacts with soil moisture storage and extraction to affect the level of stress occurring. Shaw and Laing [26] found that stress is more likely to develop when transpiration is high in relation to soil moisture content in the neighborhood of one bar suction. Shaw [25] observed that, in general, the evapotranspiration relative to that when soil is at field capacity decreases with the decrease in available soil moisture (Fig. 27).

The geometric relationship known as Boulé principle has been suggested by Hall and Butcher [12] and good verification was found in an analysis of India Agricultural Research Institute finding reported in the study report of a joint Indian-American Team [16]. The formulation is based on the principle that a water deficiency at any stage of growth of a crop has an effect on the agronomic features and yield of the crop.

Define the measure of soil moisture deficiency as the relative actual evapotranspiration to potential evapotranspiration. Call this measure when it occurs during the i<u>th</u> growth stage d_i. Let the maximum yield, obtained under the optimal moisture regime, be defined by yield_m and let the yield resulting from a moisture stress during the i<u>th</u> growth stage be defined by yield_i. These two yields are related through a function coefficient a_i which is a function of d_i hence

$$\text{yield}_i = a_i(d_i) \cdot \text{yield}_m \tag{20}$$

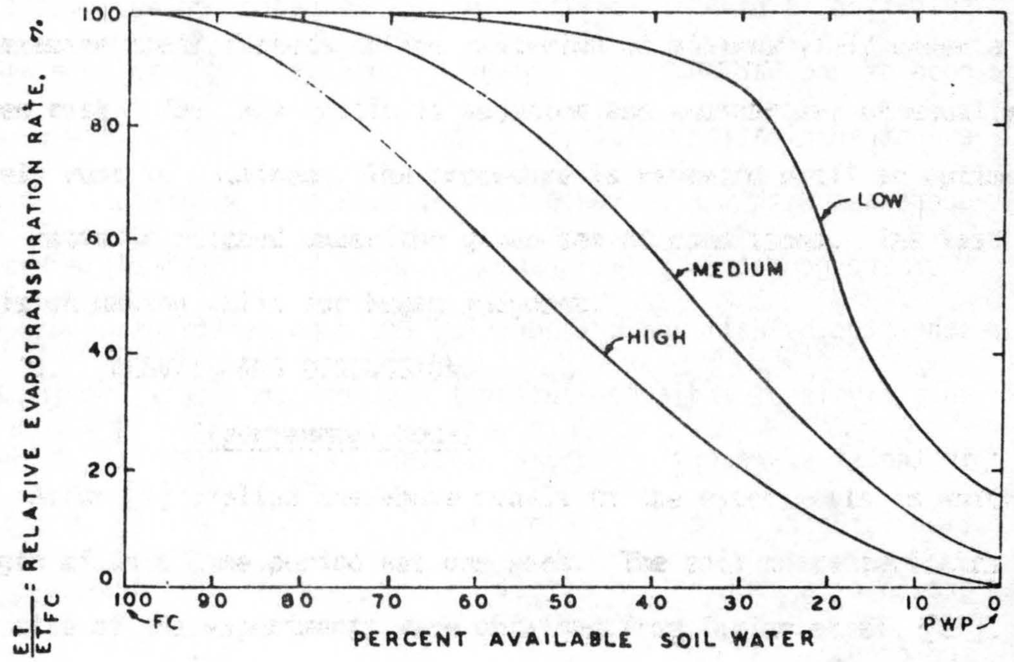


Figure 27. Ratio of Actual Evapotranspiration to Evapotranspiration at Field Capacity at Different Levels of Soil Water for Three Atmospheric Demand Conditions (Shaw, 1963)

Assume there are n stages of growth for the crop in question, then the yield resulting from deficiencies during these stages is defined by

$$\text{yield}_{1,2\ldots n} = a_1(d_1) \cdot a_2(d_2)\ldots a_n(d_n) \cdot \text{yield}_m \qquad (21)$$

Let a new variable, R, denote the relative yields resulting from water deficiency, to the maximum possible; i.e., $R = \text{yield}_{1,2\ldots n}/\text{yield}_m$. Thus Equation 21 may be described as

$$R = \prod_{i=1}^{n} a_i(d_i) \qquad (22)$$

For the purpose of clarity and avoiding the mathematical abstractness, consider the case where $n = 2$; or the crop has two stages of growth. The relative yield is then given by

$$R = a_1(d_1) \cdot a_2(d_2) \qquad (23)$$

d_1 and d_2 may be represented by the x- and y-axis and the relative yield, R, by the z-axis.

Asfur [1] using the relative yield function of Equation 23 as developed by Hall and Butcher [12] showed that it could be expressed by

$$R = \exp\{\int f_1(d_1)dd_1 + \int f_2(d_2)dd_2\} \qquad (24)$$

Generalizing Equation 24 for the n dimensional case, Asfur [1] expresses the relative yield function as

$$R = \{\sum_{i=1}^{n} \int f_i(d_i)dd_i\} \qquad (25)$$

Using available information on yield and soil moisture regime of different fields, it would be possible to evaluate the above function.

The resulting formulation would then be used to estimate the yield under the simulated moisture regimes using the soil water balance model.

The above models are linked and used sequentially in estimating yield under a specified x/y ratio. The resulting yields from several equally likely rainfall and evaporation conditions would be analyzed to examine their fitness to the criterion of minimum yield under a given risk. The x/y ratio is adjusted and another set of equally likely runs is obtained. The procedure is repeated until an optimum x/y ratio is reached under the given set of conditions. The last decision making calls for human judgment.

B. RESULTS AND DISCUSSION

1. Experimental Model

Asfur [1] applied the above models to the experiments in which the length of unit time period was one week. The soil characteristics of the site of the experiments were obtained from Taylor et al. [27]. The crop that was modeled was winter wheat with total growing period of 35 weeks spanning roughly the period from the last week of October through June. As measure of water deficit, the water use per treatment per week was divided by the maximum water use in that particular week. This was done under the assumption that this maximum water use represents the potential evapotranspiration. The crops in the rest of the treatments would have used the same quantity had the water been available to them in the same magnitude. In the model, the 35 weeks were divided into five periods, each representing two stages of growth. The first stage of 20 weeks period contains the agronomic stages of emergence and tillering. The second stage of four weeks contains the jointing stage. The third and fourth stages of three weeks each are the boot and flower stages, respectively. The last stage of five weeks is the milk, soft dough and maturity stages.

2. Results of Model Simulation

For each of the defined stages of growth and in each treatment, the arithmetic mean of the relative water use (the defined measure of water deficit) was calculated and used to represent the stress in that particular stage of that particular treatment. Since the data used in this study were obtained from moisture (M) and fertility (F) treatments, it was necessary to eliminate the effect of fertility and the effect of the season. For each season of growth, the 18 treatments were divided into three sets, each of a fertility level; i.e., each set contained the results of the six moisture levels which were at the same given fertility level. The *relative yield* was obtained by dividing the yield of each by the maximum one in that particular set. The *averages* of relative water use and relative yield of each treatment in each season were used as input data to the *crop response function analysis* and are presented in Table 11 for the 1955-56 season.

The result of the crop response function analysis is a set of intercepts and slopes of the straight line describing the points in each hull at each stage of analysis. The *ratio* of slope to intercept was taken for each hull that contained enough points (d_i) and plotted against the points around which expansion was done.

Polynomials of various degrees were fitted to these points and the results of best fit to the equation $k_i/k_o = f_i(d_i)$ $i = 1,2...n$ are the following:

$$\frac{k_1}{k_o} = -4.36 + 6.90\ d_1$$

Table 11. Water Deficit Measures and Relative Yield for Winter Wheat Considering Five Stages of Growth, 1955-56 Season (Asfur, 1972)

		Deficit Measure					Relative
		Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Yield
M1	F2	0.900	0.504	0.413	0.279	0.404	0.503
	F4	0.982	0.497	0.444	0.270	0.441	0.334
	F5	0.939	0.573	0.474	0.183	0.441	0.417
M2	F2	0.900	0.450	0.608	0.332	0.404	0.664
	F4	0.982	0.466	0.663	0.278	0.478	0.516
	F5	0.939	0.665	0.675	0.270	0.441	0.563
M3	F2	0.900	0.504	0.488	0.517	0.434	0.872
	F4	0.982	0.497	0.466	0.502	0.529	0.819
	F5	0.939	0.573	0.596	0.610	0.642	0.889
M4	F2	0.900	0.450	0.479	0.762	0.515	1.000
	F4	0.982	0.466	0.749	0.889	0.735	1.000
	F5	0.939	0.665	0.611	0.711	0.846	1.000
M5	F2	0.921	0.668	0.617	0.759	0.706	0.908
	F4	0.964	0.626	0.935	0.711	0.933	0.975
	F5	0.921	0.730	0.878	0.962	0.904	0.993
M6	F2	0.900	0.450	0.479	0.813	0.614	0.952
	F4	0.982	0.466	0.749	0.762	0.460	0.815
	F5	0.939	0.665	0.611	0.711	0.601	0.912

M1 to M6 are six irrigation treatments.
F2, F4, and F5 are three fertility treatments.

$$\frac{k_2}{k_o} = -7.87 + 62.42\ d_2 - 136.12\ d_2^2 + 89.98\ d_2^3$$

$$\frac{k_3}{k_o} = -0.50 + 1.01\ d_3$$

$$\frac{k_4}{k_o} = 3.04 - 4.04\ d_4$$

$$\frac{k_4}{k_o} = 48.08 - 337.26\ d_5 + 723.53\ d_5^2 - 481.15\ d_5^3$$

In the relative yield expression given by

$$R = \prod_{i=1}^{n} a_i(d_i)$$

the relationship for a_i and d_i is given by

$$a_i = e^{\int f_i(d_i)dd_i} \qquad i = 1,2...n \tag{26}$$

which is the function coefficient for relating the yield, caused by water deficiency during the nth stage, to the maximum possible yield as expressed by

$$R = a_i(d_i) \cdot a_{i+1}(d_{i+1}),\ i = 1,2...n \tag{27}$$

Carrying on the integration and exponentiation for the case study, the results to Equation 26 are

$$a_1 = \exp\{-4.36\ d_1 + 3.45\ d_1^2 + c_1\}$$

$$a_2 = \exp\{-7.87\ d_2 + 31.21\ d_2^2 - 45.37\ d_2^3 + 22.44\ d_2^4 + c_2\}$$

$$a_3 = \exp\{-0.50\ d_3 + 0.50\ d_3^2 + c_3\}$$

$$a_4 = \exp\{3.04\ d_4 - 2.02\ d_4^2 + c_4\}$$

$$a_5 = \exp\{48.08\ d_5 - 168.63\ d_5^2 + 241.18\ d_5^3 - 120.29\ d_5^4 + c_5\}$$

where the c_i's are constants of integration. Asfur [22] found that the sum of the constants of integration was approximately -4.79. He found that the relative yield equation

$$R = \{ \sum_{i=1}^{n} \int f_i(d_i) dd_i \}$$

for winter wheat may be expressed in terms of water deficiencies as

$$\begin{aligned} R = \exp\{&-4.36\ d_1 + 3.45\ d_1^2 - 7.87\ d_2 + 31.21\ d_2^2 - 45.37\ d_2^3 \\ &+ 22.49\ d_2^4 - 0.50\ d_3 + 0.50\ d_3^2 + 3.04\ d_4 - 2.02\ d_4^2 \\ &+ 48.08\ d_5 - 168.63\ d_5^2 + 241.71\ d_5^3 - 120.29\ d_5^4 - 4.79\} \end{aligned} \qquad (28)$$

Ten seasons were run with harvesting area of 25 units and cropped area of 5 units resulting with a harvesting to cropped area ratio of 5. The yield was estimated from the deficiencies obtained from the simulation model and using Equation 28. These results are presented in Table 12.

IV. SUMMARY AND CONCLUSIONS

The objective of this report has been to summarize current water harvesting technology applicable to agricultural needs in developing countries located in semiarid and/or subtropical climates. The section on methods of harvesting water considered two methods: surface treatment and use of subsurface soil strata.

Water harvesting by surface treatment included the use of chemicals and synthetic membranes for the increase of runoff from arid land

Table 12. Water Deficits and Yield of Simulated Equally Likely Seasons (Asfur, 1972)

Run	d_1 Stage 1	d_2 Stage 2	d_3 Stage 3	d_4 Stage 4	d_5 Stage 5	Yield* Bushels/Acre
1	.950	.876	.629	.429	.622	40.0
2	.890	.807	.69-	.564	.471	27.2
3	.900	.544	.737	.150	.708	19.7
4	.800	.989	.390	.250	.370	35.4
5	.742	.652	.706	.519	.480	20.7
6	.817	.604	1.000	.955	.458	26.1
7	.948	.535	.492	.917	.138	17.6
8	.887	.432	.660	.398	.219	23.9
9	.843	.906	.844	.820	.592	39.4
10	.950	.599	.918	1.000	.704	43.0

*Yield is measured per area of cropland rather than the total area.

surfaces. Water harvesting by surface treatment is now in the beginning stages of large-scale development. Techniques now under test promise to allow the collection of precipitation for average costs of approximately 20 cents per 1000 liters.

The maximum water supply which can be developed at a given location should not be based on stream flow but on precipitation. Precipitation, particularly in arid regions, is many times greater than stream flow. All of the precipitation cannot be captured, but part of it can. The amount to be collected will depend on need. Water harvesting by surface treatment will not be feasible in some areas. On the other hand, there are many areas where water harvesting offers the only reasonable opportunity to develop new water supplies. Besides the need for harvesting of precipitation is the need for proper storage and conveyance of the water for its eventual efficient use.

The other component of water harvesting by surface methods is the storage of water in compartmented reservoirs. This method of water harvesting, whether integrated with surface treatment, is a function of runoff efficiency, which is defined as the percent of total precipitation that appeared as runoff into the reservoir. Cluff [5] found that if the runoff efficiency was satisfactory the distribution of the runoff with time was also acceptable.

The concept of the compartmented reservoir lends itself to staged construction. The first compartment could be excavated and used for collecting runoff for a period of time. Measurements of rainfall and runoff could then be made to aid in the calibration of the model (CROP-76) before a final sizing of additional was made. This would also provide a source of construction water, a vital ingredient of a successful embankment construction [5].

Cluff [5] found that the model is successful in simulating activities related to pumping, or moving water from one compartment to the others, when there is sufficient unused capacity. The pumping is at discrete times in order to allow for the use of portable high-capacity pumps. Where there is sufficient topographic relief a gravity-fed compartmented reservoir can be installed. Under this system compartments, connected by pipes or elevated canals, are spaced down a slope so that the upper compartments can be completely drained into lower compartments. Spacing is dependent on the degree of slope, depth of the tank and size of the pipe.

The model also showed that the amount of water pumped for "concentration" in the operation of a compartmented system is usually less than the amount of water available for consumptive use if the water is removed at a constant rate. However, if a compartmented reservoir is used only to supply water during the dry part of the year or during drought years, the amount of "concentration" pumping would probably exceed the amount of water available for consumptive use. Furthermore, if efficient high-capacity portable pumps are used, the cost of pumping would be small in comparison to the amortization costs of the installation of the compartmented reservoir. The use of the model with systems that would store solar pumped water as well as for water harvesting agrisystems indicates the wide application of the concept of compartmented reservoirs in areas of high evaporation loss.

Cluff [5] by repeated use of CROP-76 for the Santa Cruz River reservoir in Arizona and the Goumbau and Nara reservoirs in Mali was able to examine the interrelationship of the parameters of volume, area, depth and slope of the embankment for each compartment. On the basis of the study, the following conclusions were made:

1. The rate of increase in storage efficiency is greatest when a one-compartmented system is converted to a two-compartmented system. There is an additional significant improvement when going from two to three compartments. However, the rate of increase in storage efficiency diminishes as the number of compartments increases.

2. The model did not indicate a significant difference in overall storage efficiency resulting from varying the relative size of the several compartments provided the total size as well as other factors remain constant.

3. The increase in efficiency due to the use of the compartmented system decreases as the depth of the reservoir increases, becoming insignificant at a depth of 20 or more meters.

4. The use of CROP-76 demonstrated that evaporation losses can be significantly reduced by compartmentalizing shallow impervious reservoirs and concentrating water by pumping it from one compartment to another.

As for the compartmented reservoirs, the efficiency and economy of the soil and rock strata constructed on the various Indian reservations was found to be primarily a function of the geometry of the facility. Factors to be considered relative to future sites include:

1. Choosing site locations with drainage area of a suitable size. Those in existence are larger than necessary, resulting in costly maintenance problems. Facilities of 10,000 to 20,000 gallon capacity would be more easily constructed and would, in most cases, provide an adequate water supply for most needs in remote areas. If more volume is needed, the facilities could be constructed in series with interlinking pipe systems.

2. Selecting the geometry of the facility to minimize the clogging of the interstices of the coarse-aggregate blanket by fine material carried in suspension as a wash load. For example, a long narrow basin with a shallow upstream depth on a flat gradient might minimize the loss of storage volume.

3. A sequence of construction operations that minimize earthmoving costs. The work at the Pine Ridge site, for example, was carried out in a much more expeditious manner than that earlier accomplished in New Mexico. A better fit of the design to the site topography also helped to reduce construction costs.

Expanding the concept of water harvesting to the development of an arid-farming technology has been demonstrated by the experimental program involving macrowatershed sites at the Escuela Superior de Agricultura "Antonio Narro," (ESAAN) Buenavista Saltillo, Coahuila, Mexico. Excellent crops, fully equivalent to adequate rainfall conditions, were produced with annual precipitation on the order of 200 to 300 millimeters. However, the successful application of these water harvesting techniques under a wide variety of conditions requires further research to establish the pertinent relationships, practices, and limitations of this important potential addition to the food production capability of the world.

The experimental program at ESAAN involved the on-site water harvesting systems, using contour borders or level trench terraces, where an area several meters wide serves as the watershed or runoff area. A second down-slope area serves as the crop area. The <u>ratio</u> of the two areas determines the quantity of water usefully havestable, all other things being equal. The soil volume of the crop serves as the storage reservoir for the system. The effective soil volume is limited by the rooting depth of the crop and the characteristics of the soil. For full production, this soil volume must be capable of holding sufficient moisture to meet the evapotranspiration demand between replenishments by rain storms. Since it is quite unlikely that the conditions for full production can be consistently met (because of the probability distribution of frequency and amounts of rainfall), the ability of the crop varieties to withstand occasional drought is likewise a factor. Of critical importance, therefore, is the capability of the soil on the watershed area to maximize runoff from minimum amounts of precipitation. Also of great importance is the timing of the deficit in relation to stage of growth. This suggests potential adjustments of planting dates and varietal selections which best correspond to the distribution of rainfall probabilities over the growing season, and which show more extensive root development.

The success of the ESAAN research with regard to field crop production has demonstrated the utility of the on-site water harvesting concept. Also, the results indicate the potential for further and more extensive research in water harvesting techniques in context with the specific genetic potential of drought-hardy plants such as maize and wheat, and root-extensive crops such as alfalfa or trees.

Optimization of the use water harvesting systems for field crop production and/or the harvesting of water can be achieved by means of a simulation model. Integrating the model with field tests provides a fast method of estimating the dimensions of the crop and harvesting areas. Optimizations of these dimensions can then be done very fast and without complexity. The estimation of the <u>crop response function</u> is lengthy and the dimensionality increases with the increase in number of stages, faster than the increase in the number of points of expansion. However, the resulting function is of importance and the need for such functions outweigh the roughness in the procedures and the approximations used in obtaining these functions.

V. RESEARCH NEEDS

Many, if not most, of the developing nations of the world have extensive areas in which the rainfall is substantially less than that required for normal dry-land farming operations. For some nations, these areas represent the sole remaining undeveloped agricultural resource.

Although considerable attention has been given to the development of varieties of agricultural practices under adequate moisture conditions, research leading to the development of an arid-farming technology has been virtually nonexistent. An integral part of the problem is adequate water for human consumption. Thus, this report has sought to summarize these components of water-harvesting which would, if properly integrated, address the total water needs of those people living in the developing nation. Because adequate and nutritious food has preeminence over drinking water, the use of water harvesting in the development of farming practices for agricultural production in semiarid, subtropical climates should receive the greater attention.

Essential to any agricultural research investigation will be the ability to analyze the soil-water mass balance of the water-harvesting system. Factors to be considered will include: overland flow hydrology, rainfall intensities, potential evapotranspiration, the type of surface treatment on the contributing watershed, the soil moisture at various stages of plant growth for a given plot, and the root development as a function of the soil moisture regime. Optimization of the total water harvesting system will make use of mathematical models such as CROP-76 [5] and those developed by Asfur [1].

There are a number of methods for the enhancement of surface runoff in the water collection area. The use of thin films of plastic sheeting has many disadvantages including cost, instability of the plastic sheet in wind, water channeling and erosion beneath the sheet and deterioration of the indigenous surface vegetation which, as sparse as it may be, serves to stabilize the soil. Nonorganic sealants such as bentonites and montmorillonites tend to migrate under the influence of both wind and water and could collect around the row crop plant area stifling the absorption of water in precisely the areas where it is wanted and needed. Petroleum based resin systems can be used, however, this use is limited, in developing countries, first by the excessive cost of petroleum solvent and the defoliating effect of the solvent on the indigenous surface cover. Any overspray would also have adverse effect on the row crop plants. Water emulsion systems of heavy petroleum residue such as emulsified asphalt are not satisfactory. The emulsified asphalt remains as a heavy film on the soil and agglomerates into thick lumps upon reworking the soil in the water harvesting area. From preliminary experiments at Colorado State University, it appears that one of the most practical methods of enhancing water harvesting is by the application of a hydrophobic resin emulsion at low concentrations. Emulsions can be selected that break quickly at the surface of the soil leaving a water repellent film following the natural contour of the soil. At low concentrations, i.e., 5 percent to 10 percent, these emulsion systems should not have a debilitating effect on either indigenous plants in the water harvesting area to to the row crops themselves.

The general properties desired in such a resin emulsion system are to utilize a hydrophobic resin that is not rewettable after drying or curing. It may be necessary to use an amine-resin or amine-fatty acid emulsifying agent. At the temperatures expected in semiarid, subtropical climates amine-type emulsifying agents should break down or volutalize and leave the system. Soil surface temperatures in the sun of over 140°F can be expected. For this reason, wax emulsions cannot be used as they soften and are absorbed by the soil and clay particles. It is necessary to consider high molecular hydrocarbon resins, acrylic resins, acrylic copolymers or similar systems for this application. It is not necessary to limit the consideration to resins that form continuous films as it may be possible to utilize "breather" type films which would permit the vapor transmission of water from the subsurface.

Resin systems to be investigated may be modified by blending with other emulsions to improve plasticity or water contact angle in the resulting film. In summary the factors that need to be considered in evaluating the resin systems include consideration of emulsion, types of resin, resin modifiers and methods of application.

In the storage of water harvested by surface treatment, additional research is needed to determine the effect of the compartmented reservoir or reducing water temperature and rate of evaporation loss.

More work is needed to develop design and construction procedures of gravity-fed separated compartmented reservoirs.

A suitable sediment transfer routine needs to be incorporated into CROP-76 in order to estimate the cleaning interval of the receiving compartment.

Additional data are needed to determine the relationships involved between compartmented reservoirs and seepage. This effect, when documented, can be included in CROP-76.

A detailed economical study of the compartmented reservoir system in various applications in different parts of the world needs to be made.

New construction methods may be needed to minimize the cost of constructing earthen embankments between compartments.

Additional work is justified in improving the soil moisture accounting method in the agrisystem option of CROP-76. Consideration should be given to utilizing an overland flow and infiltration routine as was done by Hanson et al. [27].

The basic feasibility of the artificial aquifer for water harvesting under difficult hydro-meteorological conditions has been experimentally established by the experiences gained in South Dakota, New Mexico, and Mexico and of the Nabbateans of the Negev Desert, subsequently substantiated by Evenari et al. [10]. However, there are important technical problems yet to be resolved to allow the development of design specifications which will reduce costs, and improve efficiency and reliability of these systems.

The principle losses of water from an artificial aquifer will be seepage and evapotranspiration. They presumably can be reduced to essentially zero by the use of impermeable membranes or by the placement of clays or other soils of very low permeability below the water bearing portions of the aquifer. Evapotranspiration on the other hand could result in the loss of as much water as would be the case for an open pond.

Of the two, transpiration can be expected to be an order of magnitude greater than the bare soil evaporation because the root systems of the plants provide a fairly efficient means of converting net radiation and convective heat inputs to the plant into evaporated water from a wet root zone falls below the permanent percentage (corresponding to a capillary tension of approximately 15 atmospheres), the plants wilt, the stomata close and transpiration drops to a very low level, approaching zero or at least that of direct evaporation from the soil.

Thus it is apparent that, to improve the yield efficiency of an artificial aquifer, it will be useful to prevent the growth of plants entirely or to limit their depth of rooting to the zone which would probably lose its moisture by evaporation in any event, or at least to some depth well above the capillary fringe of the aquifer. If roots are allowed to reach the capillary fringe, excessively high rates of evapotranspiration can be expected.

The two forms of water loss from soil surfaces are not independent. Both rely on the same radiation and convective heat transfer to provide the latent heat of vaporization of whatever water is lost. In addition if water in the interstices of the soil to some minimum rooting depth can be lost rapidly by direct evaporation, the ability of plants to become established on that soil is reduced by several orders of magnitude. Conversely if the surface soil holds moisture well above permanent wilting point for sufficiently long periods of time, plants will almost certainly become established which will have the potential to reach the water table in the artificial aquifer.

In summary, there is a need for methods to evaluate the water transport phenomena from the surface of the system so that rational design criteria can be established. One method, for example, would be to determine the net mass transport out of the system using an energy balance equation similar to that used in the Panman equation but with a heat storage term to represent the net heat addition to the soil due to raising the temperature. Another method might be to write the partial differential equations for mass and heat transfer into and out of the surface layers under a reasonable assumption of the diurnal variation of soil surface temperatures. These equations become interconnected through the heat of vaporization. Gradients would be associated with the partial pressure of the vapor pressure in equilibrium with local temperature, with temperature and with capillary pressure. The two approaches can also be combined.

One of more important aspects for longevity of the artificial aquifer is the problem of preventing excessive loss of infiltration rate at the surface of the gravel mulch by the entrapment of sediment within the pores of the gravel. The artificial aquifer is designed to be recharged from rainfall and resultant runoff.

The strategies to cope with the problem could include the following:

1. Allow the runoff water to pass on over the surface with sufficient velocity to keep the fine materials in suspension. This will require a larger watershed area per unit of aquifer volume. Since the sediment load is increased as the watershed size is increased (for the

small watershed size generally used) this can be self-defeating. This aspect is, of course, quite site sensitive and situations will exist where providing for excess runoff will allow a relatively automatic clearing of the recharge surface.

2. Design a stilling basin for the catchment from which the water is conveyed (after clarification) to the recharge area. In effect, this is a combination surface reservoir-groundwater reservoir system. For some watersheds and situations it will serve quite well. In others, however, clarification may never occur in the reservoir because of its dimensions.

3. Establish certain shallow-rooted (one foot or less) grasses on the surface of the recharge area. Such grasses have evapotranspiration losses only slightly higher than might be expected with bare soil surfaces. They have the property of quickly aggregating the fine particles filtered at the soil surface, thus maintaining infiltration capacity at reasonably high rates indefinitely.

Other research and development areas which will be useful in eliminating costly over design, include more precise simulation modeling of the hydrological system to assure proper treatment of extreme events. It would also be useful to determine the relative economic balance between costs of excavation and backfilling with mine run sand or gravel, on the one hand with the costs of separating out the backfill material into sizes to increase water storage capacity. Better bottom sealing methods and/or backfilling processes could also be investigated profitably, once the performance requirements can be established.

The extension of the development of farming practices involving water harvesting and crop production should begin with the selection of field sites representing different rainfall levels, soil conditions, and plant species. The scope of the research program should attempt to delineate the desirable characteristics of on-site water harvesting methodology, in the enhancement of runoff from rainfall, as a catalyst in soil moisture and fertility regimes, in the control of crop responses during growth, and as a viable parameter in estimating a relationship between final crop yields and the management practices used.

Plant species should be carefully selected to provide a wide range of rooting depths, potential drought resistance, economic utility, and potential regional adaptability.

Also of importance will be the ability to analyze the soil-water mass balance of the water harvesting system. Parameters to be considered include: overland flow hydrology, rainfall intensities, potential evapotranspiration, the soil moisture regime at various stages of plant growth for a given experimental plot, and the root development as a function of soil moisture regime. The objective of the analysis will be to optimize the selection of significant parameters for the development of transferability of data from one test site to another using the method of analysis developed by Asfur [1].

For the optimization model for water harvesting developed by Asfur [1], it is recommended that further analysis be done in refining the program for crop response function analysis by developing data reduction procedures to decrease the number of hulls to be tested. The simulation model would give more accurate results if a true function of root development is used. In the development of the model Asfur [1] assumed that root development is independent of the soil moisture regime which is not true. The coefficient of runoff should be obtained empirically for the sites under consideration. The accuracy of the crop response function should be tested in the field.

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