



An Investigation of Hydrological Aspects of Water Harvesting

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AN INVESTIGATION OF HYDROLOGICAL
ASPECTS OF WATER HARVESTING

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PREFACE

This report concludes Project B-071-TEX of the Texas A&M University Water Resources Institute. Project results have not yet been published in scientific journals. Reprints of such publications will be supplied to OWRR as they become available.

Appreciation is expressed to Mrs. Grace Smith and Mrs. Theo Doerge, past and current bookkeepers for the Texas A&M University Water Resources Institute and to Mrs. Martha Hyde, secretary, for their aid and patience.

Appreciation is expressed to Esso Research and Engineering Company for donating some of the crude oils used in this study.

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DESCRIPTION OF SYMBOLS

- A = the cross-sectional area of the stream in ft^2 ,
 f = intake rate in in./hr or ft/sec at any time,
 f_c = the final intake rate, in./hr,
 f_o = the initial intake rate, in./hr,
 h = water surface depth in ft,
 h_L = water surface depth at the downstream edge of the overland flow slope, ft,
 k = constant in the Horton infiltration equation,
 n_c = Manning's roughness coefficient for the channel (English units),
 n_w = Manning's roughness coefficient for the valley walls (English units),
 p = rainfall in ft/sec,
 Q = the quantity of flow in ft^3/sec ,
 q = overland flow quantity in ft^2/sec ,
 q_L = overland flow quantity at the downstream edge of the overland flow slope in ft^2/sec ,
 q_w = overland flow entering the channel stream in ft^2/sec ,
 R = the hydraulic radius of the stream in ft,
 S_c = the channel slope of ft/ft,
 S_w = slope of the valley walls in ft/ft,
 t = time in hr or sec,
 v_o = lateral inflow in ft/sec,
 W = the top width of the stream in ft,
 x = horizontal distance from upstream end or edge of slopes, ft,
 y = difference between measured and calculated runoff values, ft^3 .

ABSTRACT

Water harvesting is a potential source of water for arid and semi-arid lands. The objectives of this study were to determine combinations of land surface treatments and land forming which result in efficient but inexpensive water harvesting catchments and to determine the optimum shape of catchments.

In laboratory studies with inexpensive materials, crude oils exhibited the best sealing properties. However, by six months after application, 750 gal per ac of crude oil had no apparent effect on runoff from field plots.

Water harvesting catchments constructed by grading the soil to form V-shaped valleys and then compacting the surface yielded runoff equal to 31 to 43 percent of all precipitation. After rains, sand blown from such catchments may damage tender downwind vegetation. Some water erosion occurred, but, after two years, the basic shape and the performance of the catchments had not been damaged by erosion. Chemical weed control is recommended.

Hydrographs were successfully modeled by the kinematic wave method. Hydrologic parameters were estimated by a univariate procedure. The initial infiltration of the soil surface had the greatest effect on the amount of runoff. Thus, additional or repeated compaction may be the best practice for increasing runoff from such surfaces. Surface roughness had little effect on the amount of runoff.

The results of hydrograph simulation indicate that catchments should be as narrow as can be constructed easily with conventional equipment. A

catchment width of 16 ft may be about optimum. Catchment side slopes should be between 0.1 and 0.2. Generally, catchments should be no more than 1/8 mi long. With these side slopes and lengths, channel slopes can be as little as 0.002 without causing excessive loss of runoff. To prevent erosion, channel slopes should not exceed 0.005. Catchment surfaces should be wetted by rain or by sprinkling before rolling. Surfaces should be rolled with a rubber-tired roller for 1.5 to 3 hrs per ac. Drop structures should be installed at elevation changes to prevent erosion.

The cost of constructing graded catchments should be \$55 per ac or less. The cost of harvested water is expected to be about \$8.00 per ac-in. Efficiently-utilized natural runoff should be less expensive water.

CHAPTER I

INTRODUCTION

In a November 1968 address to the Annual Water for Texas Conference (13), Leon W. Hill, the Regional Director of the Bureau of Reclamation at Amarillo, discussed the water supplies of the Texas High Plains. He stated that Texas has already fully developed her share of Canadian River flows. Ground-water levels are declining. The Texas High Plains agricultural production is expected to peak at \$2.6 billion by 1980 and the decrease to \$1.6 billion by 2020. Hill stated that "It is obvious that augmentation of the available water supply in this area must be accomplished in the not too distant future if the currently healthy economy can be expected to maintain a normal rate of growth."

Because the Canadian River flows are appropriated, Texas and New Mexico municipalities which obtain water from diminishing ground water supplies may soon need to develop additional water supplies. The Bureau of Reclamation and the Army Corps of Engineers are considering the importation of water to the Texas High Plains from the Mississippi River system. However, legal, political, or economic barriers may prevent or delay such importation.

Water harvesting is a potential source of water for arid and semi-arid lands. In a region receiving 18 in. of precipitation annually, the precipitation falling on one section of land, 640 ac, would supply the water requirements of a municipality of about 10,000 people.

Water harvesting is currently being used to obtain household, livestock, and wildlife water supplies in the United States, water supplies

for the British Protectorate of Gibraltar, and irrigation water supplies in Hawaii (18,23,24). According to Evenari et al. (7,8) the practice was used in the Negev Desert over 4000 years ago to obtain irrigation water. The farmers cleared hillsides of rock and gravel to increase runoff and conveyed it to the cultivated field at a lower elevation. Geddes (10) states that this practice was highly developed in Ceylon during the 12th Century.

Geddes (10) reported the results of a recent water harvesting project undertaken in Australia to study the economy of a self-contained irrigation system dependent on farm runoff. An entire 400-ac farm was made into a watershed using drains and 200 ac-ft of reservoir storage at a cost of approximately \$56 per ac-ft of storage

Myers (22,23,24,25,26) has reviewed the materials which have been used to treat the soil surface to increase runoff. These include concrete, asphaltic concrete, soil cement, sheet metal, plastic and artificial rubber sheets, asphalt, and asphalt covered with aluminum foil.

Most soil treatments are designed to produce a surface completely impermeable to water. Lauritzen (17) has constructed steel catchments. Lauritzen (16) and Lauritzen and Thayer (18) have utilized butly liners to trap rainfall. Cluff (3) and Cluff et al. (5) have investigated the feasibility of gravel-covered plastic catchments and Myers (24,27) has led in the development of sprayed asphalt surfaces for harvesting water. Many of the problems peculiar to each of the treatments have been solved by these researchers. Each treatment, however, is expensive. Sprayed asphalt pavements have been constructed by Myers et al. (27) at a cost of

\$.73 per sq yd. Cluff et al. (5) installed a 0.5 ac gravel-covered catchment for \$500.

Less expensive treatments which do not form a completely impermeable barrier to infiltration have been studied. Kemper (15) reports some success with sodium chloride in increasing runoff. A sodium chloride-treated surface was studied by Cluff and Dutt (5). Of a 2.9-in. rainfall, 10.3 percent was measured as runoff from the treated plot compared to less than 0.4 percent from the control. Myers (23) reports that soil concrete has been used for water harvesting structures. Myers (23) has also used silicone to increase runoff. Generally such less expensive surfaces are not completely stable, and erosion is a continuing problem.

The efficiency of water harvesting surfaces which are not completely impermeable depends on hydrologic parameters such as surface slope, slope length, infiltration, and rainfall duration and intensity. Linsley, Kohler and Paulhus (20) describe methods for modeling overland flow which include the above mentioned parameters. Richardson et al. (32) used a routing technique to predict storm hydrographs from small basins. Wei (34) has synthesized overland flow by obtaining numerical solutions to the equations of motion describing such flow. Wei utilized an explicit finite difference scheme. Liggett and Woolhiser (19) have outlined procedures for obtaining difference solutions of the equations describing shallow water flow. Burman and Black (1) described a technique for inferring hydrologic parameters from plot runoff data. They utilized a model derived from kinematic wave theory.

The objectives of this study were to determine combinations of land surface treatments and land forming which result in efficient but

inexpensive water harvesting catchments and to determine the optimum shape of catchments.

The results of an evaluation of treatments for partially sealing soil surfaces are described in Chapter 2. Chapter 3 is a description of prototype water-harvesting catchments which were constructed by shaping the land surface. The model for the simulation of hydrographs is presented in Chapter 4. Hydrographs were simulated (Chapter 5) for conditions not present in the field. Both field and computer tests were used in choosing recommendations for the design of water-harvesting catchments. Alternatives for storing harvested water till use are discussed in Chapter 6.

CHAPTER 2

MATERIALS TRIALS

The first part of this study involved a laboratory evaluation of treatments for partially sealing land surfaces. Hydraulic and hydrologic parameters describing each surface were to be determined by simulating rainfall onto the surface of soils contained in individual trays. These attempts were unsuccessful. Cracking of soil surfaces occurred because of movement of the trays and nonuniform compaction of the soils. Also, it was difficult to construct surfaces with comparable and uniform microrelief conditions. Consequently, the various surface treatments were compared by observing the beading and infiltration of water applied to portions of the prepared surfaces.

Materials for surface sealing were applied at rates such that the projected materials costs would be less than the cost of the gravel-covered plastic catchments described by Cluff et al. (5). Surfaces were prepared by incorporating calcium oxide, cement, feedlot manure or sodium hexametaphosphate into a clay loam soil and at various rates. Surfaces were wet and compacted after the incorporation of the various materials. Surfaces were prepared by spraying crude oils or cement solutions on smooth, compacted soil surfaces. Surfaces were prepared by painting a mixture of molten sulfur, plasticizer and glass fibers on smooth, compacted soil surfaces. Various combinations of materials were tried.

Of the materials studied, crude oils appeared to exhibit the best sealing properties at the lowest cost. When oils were applied at the rate of 450 gal per ac or at higher rates, water beaded on the surfaces even after the surfaces had been exposed to sunlight for 60 days. The

sealing properties of the oils appeared to improve as the viscosity values increased from 1.1 to 4.5 ft^2/sec at 100° F.

The incorporation of calcium oxide did slightly reduce the rate of infiltration of water into soils. Little or no beneficial effect was obtained from treatment with cement, manure, or sodium hexametaphosphate. Surfaces constructed by spraying cement solutions did restrict water infiltration, but the surfaces were fragile. Mats of sulfur and glass fibers were impermeable to water. However, the mats were easily separated from the underlying soil. Mats less than 1/8-in. thick were easily broken. Attempts to spray such thin layers of the molten mixture were unsuccessful.

Although crude oil surfaces initially shed water, data presented in Chapter 3 show that under field conditions the beneficial effect is soon lost. Consequently, the conclusions drawn following this portion of the study may well be inapplicable to field conditions.

CHAPTER 3

FIELD INSTALLATIONS AND DATA

Field Installations

Nine water harvesting plots were constructed on a 2.5-ac site. A variety of situations was desired to facilitate future simulation of hydrographs from catchments not constructed. The plots are 411-ft long. Plots are 16-, 24-, and 32-ft wide. Each plot is a V-shaped channel constructed with a road grader during the fall of 1970. Channels were constructed with uniform side slopes. Several months after construction, the side slopes were measured at 12 locations in each plot, and the values were averaged to determine the side slope of each plot. The average slope along the length of the plots is 1 percent. During and after the grading, the soil surfaces were wet by a water truck and compacted by a 10-ton rubber-tired roller. A 1 ac-ft pit was constructed to collect the runoff. One plot was discarded because a drainage ditch had to be constructed to bypass natural runoff.

Fig. 3.1 is a sketch of the plot layout, collection ditch, and pit. Fig. 3.2 is a photo of the catchment surface. The widths and measured side slopes of the plots are given in Table 3.1.

Table 3.1. Geometry of prototype water harvesting catchments, Lubbock, Texas.

Plot Number	1	2	3	4	5	6	7	8
Width, ft	32	32	32	25	24	24	16	16
Side Slope	0.134	0.084	0.079	0.114	0.104	0.076	0.112	0.097

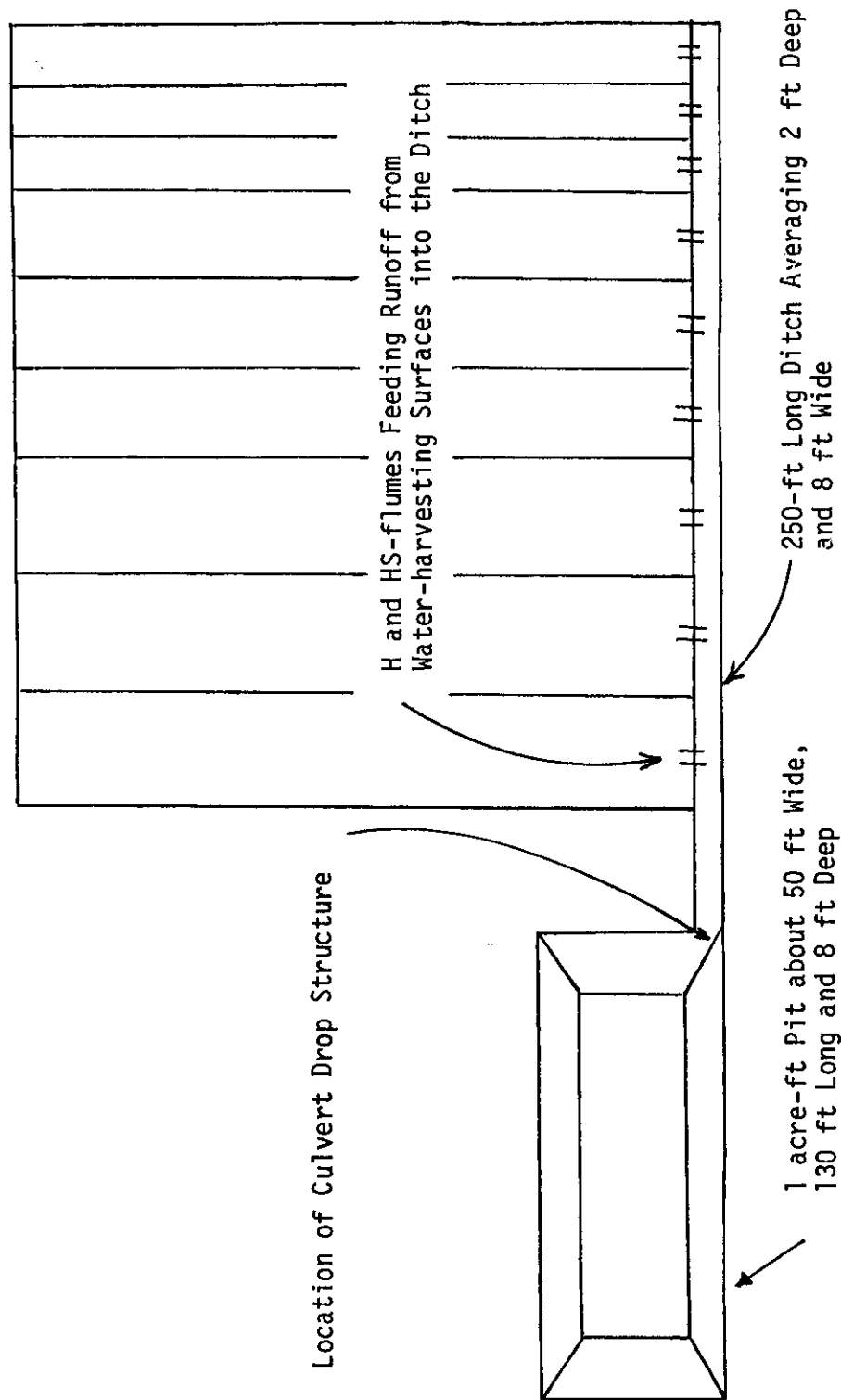


Fig. 3.1. Layout of field catchments, Lubbock, Texas.



Fig. 3.2. View of graded water-harvesting catchments, Lubbock, Texas.

Compaction resulted in a bulk density of 1.7 in the top 6 in. The same bulk density was achieved in a Proctor test.

One plot received no other treatment. On the remaining 8 plots, 85 percent of the area was sprayed with 1 of 4 crude oils. The oil application rate was 750 gal per ac in each case. Oils were applied during January, February, and March 1971.

Plots were instrumented with H and HS flumes and water level recorders. Flumes were calibrated in place.

Runoff Data

Runoff from the prototype water harvest plots has been observed since May 27, 1971. The total precipitation from May 27 through October 31, 1971, was 17.75 in. The percentage of that rainfall occurring as runoff from 8 plots is shown in Fig. 3.3. The data in the figure illustrates two facts: First, runoff increases as the side slope of the V-shaped channels, or valleys, increases; and secondly, the rate of increase with slope increases as the plot width is decreased from 32 to 16 ft. However, data obtained from simulation of hydrographs do not support the second finding.

Runoff data for individual rains is shown in Table 3.2. Occasionally hydrographs were not obtained because clocks were not wound, pen traces were incomplete, or wind-blown trash blocked flume entrances or throats. Flume blockage by trash caused some of the variability of the data. A complete data set was obtained for Plot 1. Missing data for other catchments were obtained from graphs of Plot 1 runoff vs measured runoff from other catchments.

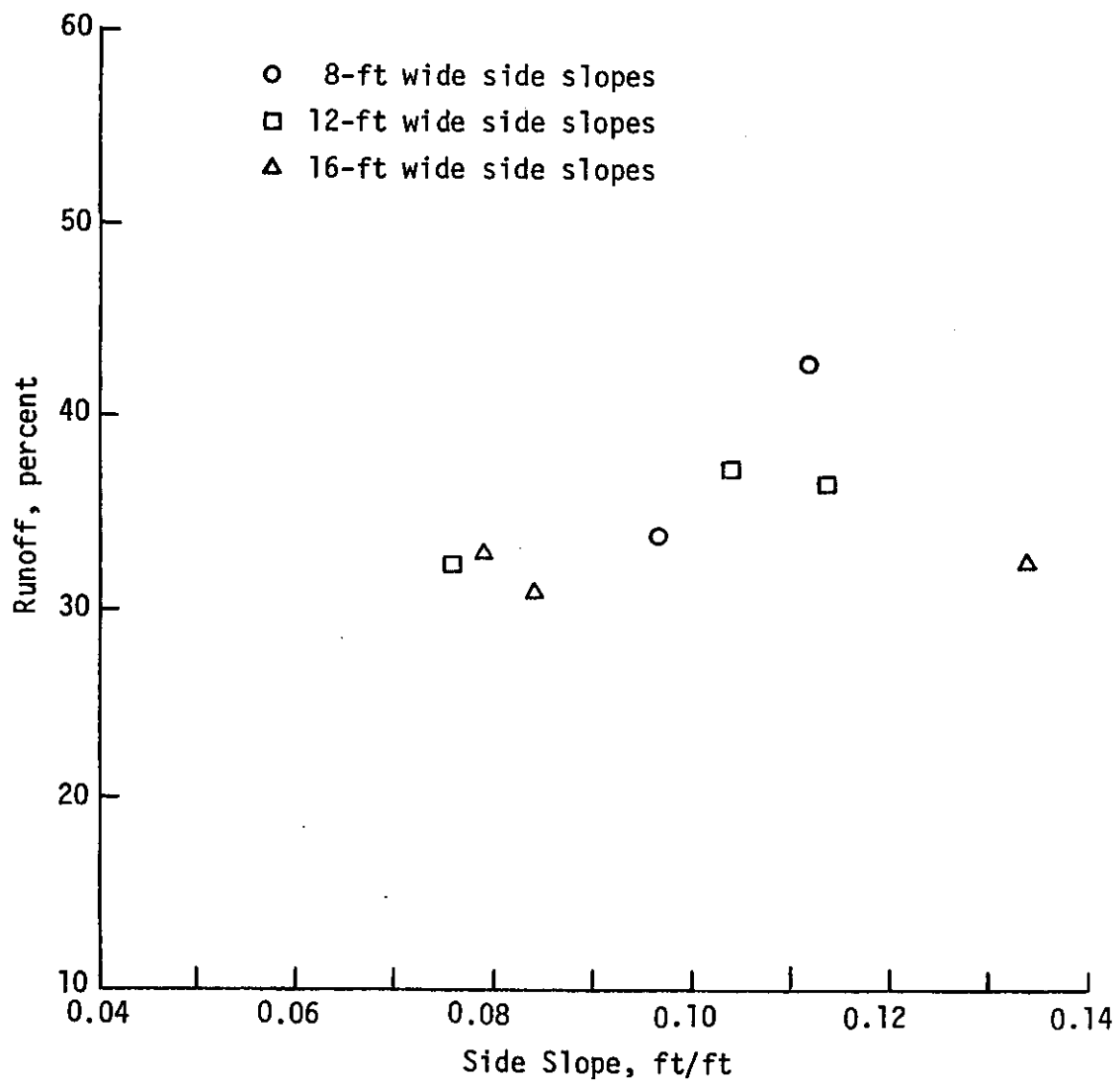


Fig. 3.3. The percentage of the total rainfall which was harvested as runoff from 410-ft long plots between May 27 and Oct. 31, 1971. Total rainfall for the period was 17.75 in.

Table 3.2. Runoff data for individual runoff-producing rains. (See Table 3.1 for plot slope and widths.)

Date	Rainfall Amount in.	Average Intensity in./hr	Percent Runoff by Plot							
			1	2	3	4	5	6	7	8
May 27	0.20	0.75	11.7	15.3	18.6	16.0	14.4	26.2	35.0	21.5
May 28	0.55	0.51	30.4	27.6	31.6	32.4	39.4	37.2	31.0	32.0
May 30	1.25	0.71	60.6	67.3	56.4	69.7	80.9	61.6	99.2	41.2
June 5	0.75	0.50	33.5	40.8	40.0	50.0	42.8	46.0	53.0	37.0
June 10	0.30	0.90	19.4	42.5	34.3	37.7	41.2	32.4	48.0	23.7
June 11	0.25	0.27	16.2	16.7	13.4	19.9	21.6	13.0	23.7	19.6
June 19	0.90	0.32	25.4	26.3	24.3	47.2	28.4	23.9	32.8	16.9
Aug. 13 ^{a/}	0.18	0.54	37.8	44.5	20.5	44.9	38.9	27.2	37.9	41.0
Aug. 15	0.10	0.60	23.8	7.8	1.5	19.5	10.5	13.5	22.1	14.8
Aug. 15	0.79	0.26	16.6	15.7	7.3	21.4	23.7	18.2	27.6	23.5
Aug. 16	0.25	0.30	34.5	25.0	24.5	52.7	27.0	38.5	54.0	33.8
Aug. 17	0.10	0.50	4.0	0.	0.	8.6	0.	0.	7.0	0.
Aug. 18	0.55	0.42	65.0	71.0	65.5	32.0	76.0	62.1	91.9	78.0
Aug. 22	0.20	0.80	65.7	30.3	23.3	82.0	43.7	22.7	36.0	65.0
Aug. 22	1.20	0.93	65.6	72.6	78.6	91.0	74.2	44.2	92.5	103.8
Aug. 23	0.15	0.45	29.8	20.3	24.1	32.7	39.8	26.6	43.1	74.0
Aug. 23	0.15	0.75	38.2	21.8	32.0	46.7	43.7	18.9	41.0	54.4
Sept. 22	0.50	-	40.6	25.6	38.4	51.5	36.6	34.6	53.2	43.3
Sept. 24	4.45	0.10	37.7	24.3	44.0	28.8	40.1	39.0	38.6	31.1
Oct. 18	1.50	-	37.1	50.3	22.2	52.0	41.9	44.7	59.3	35.3
Oct. 26	0.45	2.70	38.5	34.4	50.1	48.9	43.3	44.5	51.8	66.6
Total percent runoff ^{b/}			32.4	30.8	32.8	36.3	37.1	32.1	42.8	33.7

a/ This rainfall was preceded by a series of light showers beginning on Aug. 7, 1971.

b/ Runoff expressed as a percentage of all precipitation including rains which did not produce any runoff.

By the summer of 1971, there was no visible difference between areas which were sprayed with crude oil and unsprayed areas. The data in Table 3.3 indicate that no difference existed in runoff from treated and untreated portions of the plots.

Table 3.3. Percentage of rainfall collected from dry 4- by 6-ft plots during and following 1 in. of simulated rainfall. Tests were conducted 16 months after treated areas were sprayed with 750 gal of oil per ac.

Plot	1	2	3	4	5	6	7	8	Average
Treated	12	3	2	6	7	4	17	12	7.9
Untreated	8	7	11	8	10	4	16	7	8.9

The runoff water collected in the pit contained from 500 to 1000 ppm sediments immediately after rainfall. Some of these sediments were obtained from erosion of the collection ditch at the pit entrance. Only small amounts of ions were present in the runoff water (Table 3.4). Electrical conductivity was only 170 μ mhos per cm.

Table 3.4. Amounts of ions present in harvested water.

Ion	NO ₃ -N	Cl	Mg	NH ₃	SO ₄	Ca	Na	K
Concentration, ppm	0	0	0	0	6	16	3	3

Erosion has not caused any major change in either the shape or the smoothness of the compacted soil surfaces. Some erosion of the overland

slopes and the channels has occurred. The channel erosion is the more apparent. After rains, winds blow sand from the catchment surfaces. Unprotected downwind tender vegetation in the area of such blowing sand would be killed.

In summary, the field data show that the effect of 750 gal per ac of crude oil was soon lost due to degradation or erosion. Runoff amounts ranged from 31 to 43 percent of all precipitation. Runoff increased with increasing catchment side slope. The sediment content of the runoff was equal to that of natural runoff. Otherwise, the quality of the runoff water was excellent.

CHAPTER 4

MODEL FOR SIMULATION OF HYDROGRAPHS

Introduction

To determine the effects of hydrologic parameters on runoff, it was desired to simulate hydrographs for more conditions than could be incorporated in field plots. To do this required the choosing of a hydrologic model and the determining of the values of the model's parameters. The kinematic wave model with infiltration described by Horton's equation was chosen for the hydrologic model. A univariate method used by Burman and Black (1) was selected for estimating the values of parameters.

The Hydrologic Model

The hydrologic model used was the kinematic wave model as utilized by Burman and Black (1). Flow across the side slopes of the harvesting valleys was assumed to be one-dimensional. Flow along the length of the valley was assumed to be two-dimensional. In both cases, calculations proceeded from the upstream point and backwater effects were ignored.

For one-dimensional flow, the hydrologic model is defined by Equations 1 through 4.

$$f = (f_0 - f_c)e^{-kt} + f_c, \quad (1)$$

$$v_0 = p - f, \quad (2)$$

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = v_0, \text{ and} \quad (3)$$

$$q = \frac{1.49}{n_w} h^{5/3} S_w^{1/2} \quad (4)$$

(See page vi for symbol descriptions.)

Eq. 1 is Horton's infiltration equation. Eq. 3 is the continuity equation and Eq. 4 is the momentum equation in the kinematic wave model. The finite difference approximation used by Burman and Black (1) was used in this work with

$$h(x, t + \Delta t) = v_o \cdot \Delta t + h(x, t) + \frac{\Delta t}{\Delta x} (q(x - \Delta x, t) - q(x, t)) \quad (5)$$

$$q(x, t + \Delta t) = \frac{1.49}{n_w} S_w^{1/2} \cdot h(x, t + \Delta t)^{5/3} \quad (6)$$

Initial flow and depth are zero. Depth and flow rate at the upstream boundary are zero.

The same model and the same initial boundary conditions were used for the two-dimensional channel flow with the continuity and momentum equations given by Eqs. 7 and 8,

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_w + W(p-f) \quad (7)$$

$$Q = \frac{1.49}{n_c} AR^{2/3} S_c^{1/2} \quad (8)$$

(See page vi for symbol descriptions.)

For two-dimensional flow, the finite difference approximation used is given by Eqs. 9 and 10,

$$A(x, t + \Delta t) = (q_w + (p-f) W(x, t)) \Delta t + A(x, t) + \frac{\Delta t}{\Delta x} (Q(x-\Delta x, t) - Q(x, t)) \quad (9)$$

$$Q(x, t + \Delta t) = \frac{1.49}{n_c} A(x, t + \Delta t)(R(x, t + \Delta t))^{2/3} S_c^{1/2} \quad (10)$$

W and R are functions of A and channel shape.

Calculations

For overland flow Burman and Black (1) used a length increment Δx of 10 ft and a time increment of Δt of 15 sec. The water harvesting valleys were in some cases less than 10 ft wide. Because the valleys were symmetrical, the overland flow was calculated for only one side of a valley. The length increment Δx used for this study was 1/4 of the length of the overland flow slope; that is, 1/8 of the width of the water harvesting catchment.

With this choice of Δx , occasionally solutions were unstable with values of Δt less than 1 sec. Dr. D. A. Woolhiser (35) suggested that a variable Δt be used. Henderson and Wooding (12) specify the maximum value of $\Delta t/\Delta x$ which will insure a stable numerical solution. For this study, the value of Δt chosen was

$$\Delta t = \frac{(\Delta x)(h_L)}{2q_L}, \quad (11)$$

where q_L and h_L are the downstream flow and flow depth at time t . However, in no case was the value of Δt allowed to exceed 20 sec. Eq. 11 gives values of Δt which are about 15 percent less than the maximum values specified by Henderson and Wooding (12).

The same value of Δt was used in routing the two-dimensional flow. A check was incorporated into the computer program to insure that this

value of Δt would result in a stable numerical solution for the two-dimensional case. The water harvest catchments constructed in the field were 411 ft long. For routing the channel flow, the value chosen for Δx was 41.1 ft or 1/10 of the catchment length.

The overland-flow inflow, q_w , into a channel stream of top width W , was determined by linear interpolation between calculated values of q . Checks for occurrence of supercritical flow were included in the computer program.

The calculated infiltration, measured rainfall, and measured runoff were introduced at 2.5 min intervals. Intermediate values were determined by linear interpolation.

Stability Check

To check the adequacy of the computational procedure, hydrographs were computed for two runoff events with infiltration assumed zero. Rainfall amounts for the two events were 256.0 and 301.3 ft³. Calculated runoff amounts were 252.5 and 297.3 ft³, respectively, or 98.6 and 98.7 percent of the rainfall. To reduce computer time, calculations were stopped when runoff became less than 0.1 ft³ per min. This may account for the fact that the calculated runoff was slightly less than the rainfall.

Runoff hydrographs were recomputed with Δt equal to 1/2 the value given by Eq. 11. Runoff amounts were changed less than 1 ft³ by the use of the new Δt .

The Univariate Procedure

First initial values of f_o , f_c , k , n_w , and n_c are chosen. Then, hydrographs are calculated for various values of one parameter with the

values of other parameters held constant. The value of the varied parameter which minimizes the sum of the squares of the differences between calculated and measured runoff amounts is taken as the best value. Burman and Black (1) compared runoff amounts at 5 min intervals. The writers compared runoff amounts at 2.5 min intervals. Next, one of the other parameters is varied. After all parameters have been varied, the process is repeated until the reduction in the sum of squares of the differences between measured and calculated runoff amounts is less than a prechosen value.

CHAPTER 5

SIMULATION RESULTS

Introduction

Optimum values of hydrologic parameters were determined for two runoff events. Simulated hydrographs were generated for various conditions and, from these, the effects of variations in parameter values on runoff were estimated.

Parameter Optimization

One cycle of the univariate procedure is shown for the storm of June 10, 1971 in Figs. 5.1 through 5.5. Fig. 5.6 shows that the first step of a second cycle resulted in little improvement in the calculated hydrograph. Therefore, the parameter values shown in Fig. 5.6 were selected as optimum for that storm. Parameter values for the storm of May 28, 1971 were also determined. The optimum parameter values for the storms are shown in Table 5.1. Values of f_c and k varied the least between storms. The relationships between parameter values and percent runoff or Σy^2 were similar for the two storms.

Table 5.1. Optimum values of hydrologic parameters for two storms.

Date	Catchment Width, ft	S_w	f_o	f_c	k	n_c	n_w
May 28	16	0.112	4.3	0.08	5.6	0.055	0.210
June 10	25	0.114	1.15	0.05	5.8	0.075	0.120

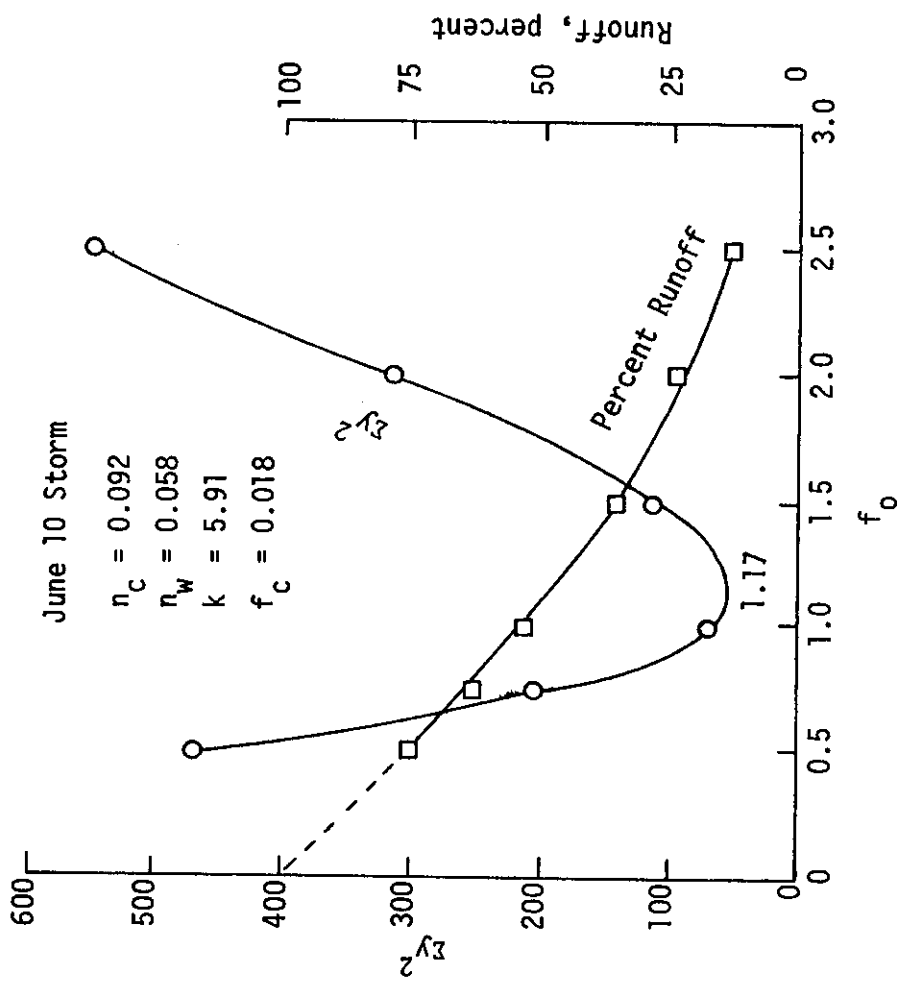


Fig. 5.1. Optimization of f_0 and the qualitative effect of f_0 on the amount of runoff. (First cycle of optimization process.)

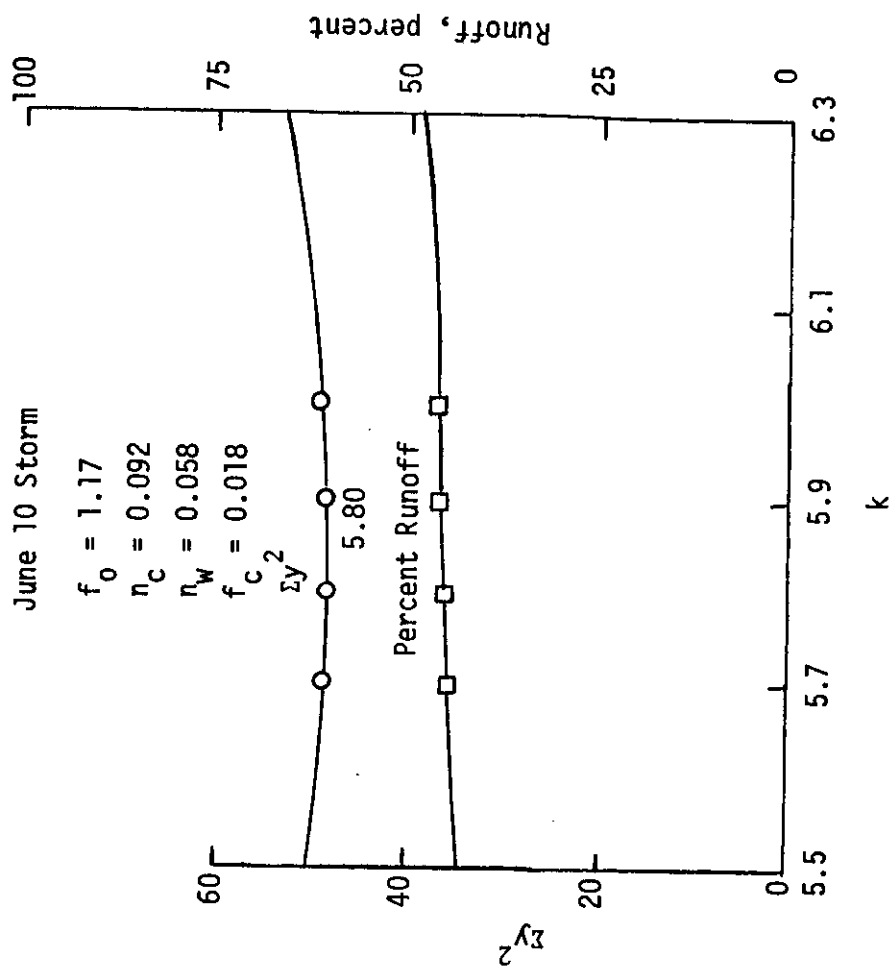


Fig. 5.2. Optimization of k and the qualitative effect of k on the amount of runoff. (First cycle of optimization process.)

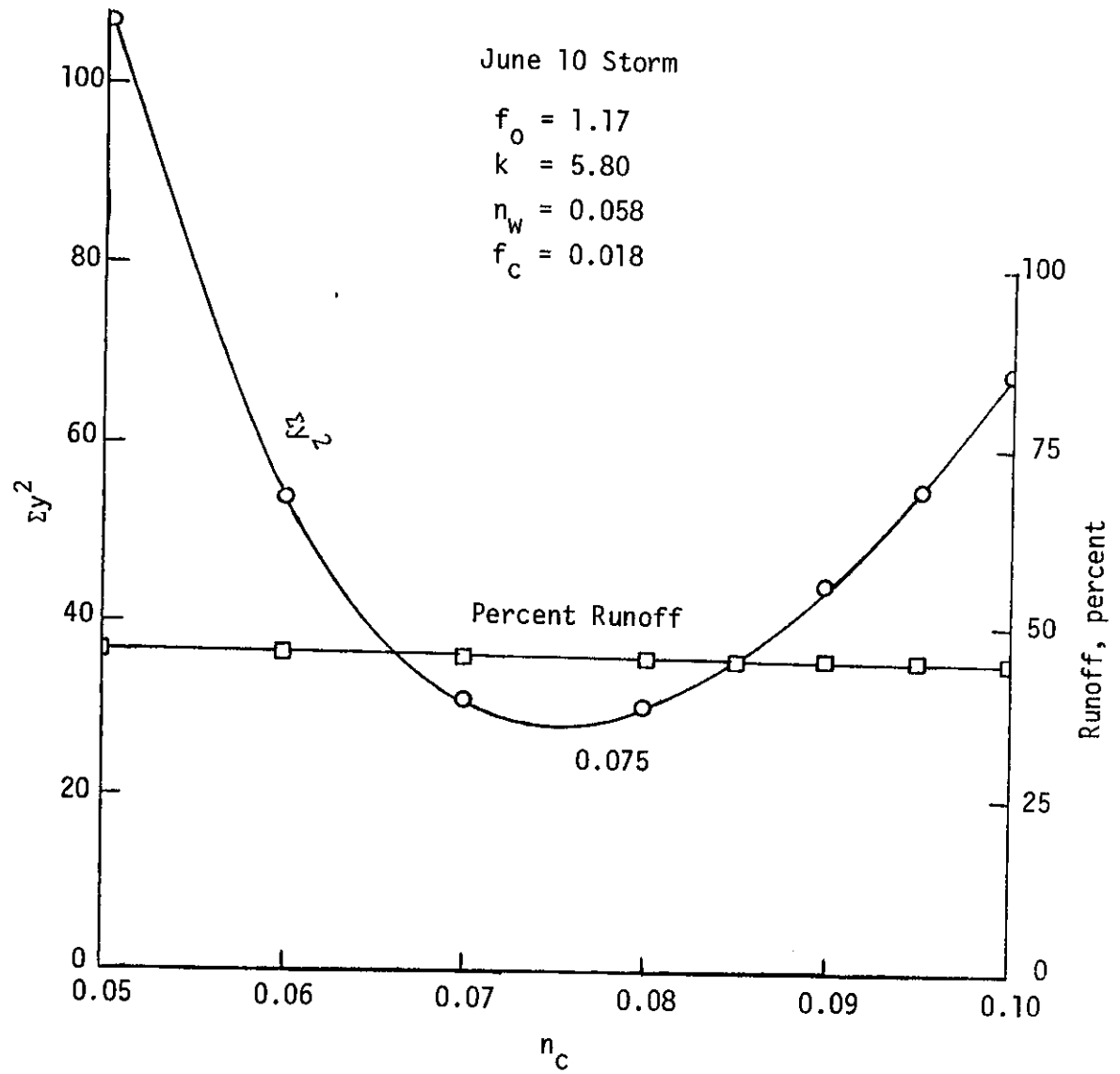


Fig. 5.3. Optimization of n_c and the qualitative effect of n_c on the amount of runoff. (First cycle of optimization process.)

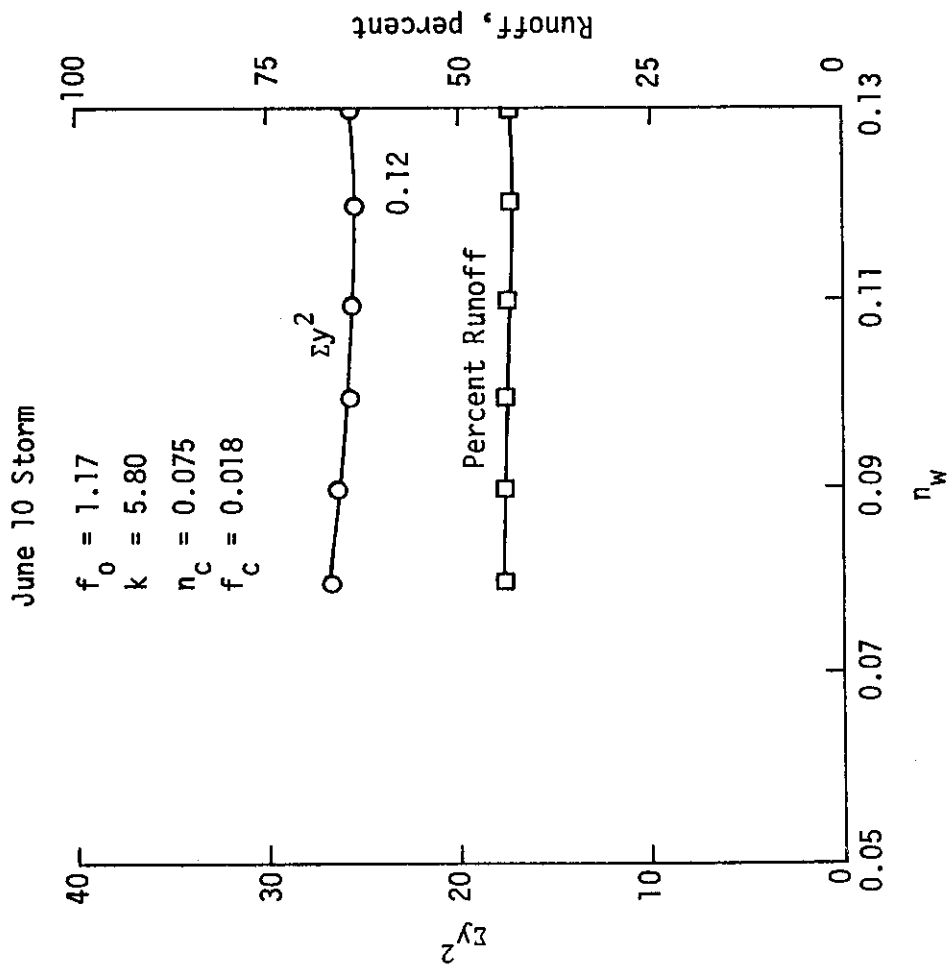


Fig. 5.4. Optimization of n_w and the qualitative effect of optimization on the amount of runoff. (First cycle of optimization process.)

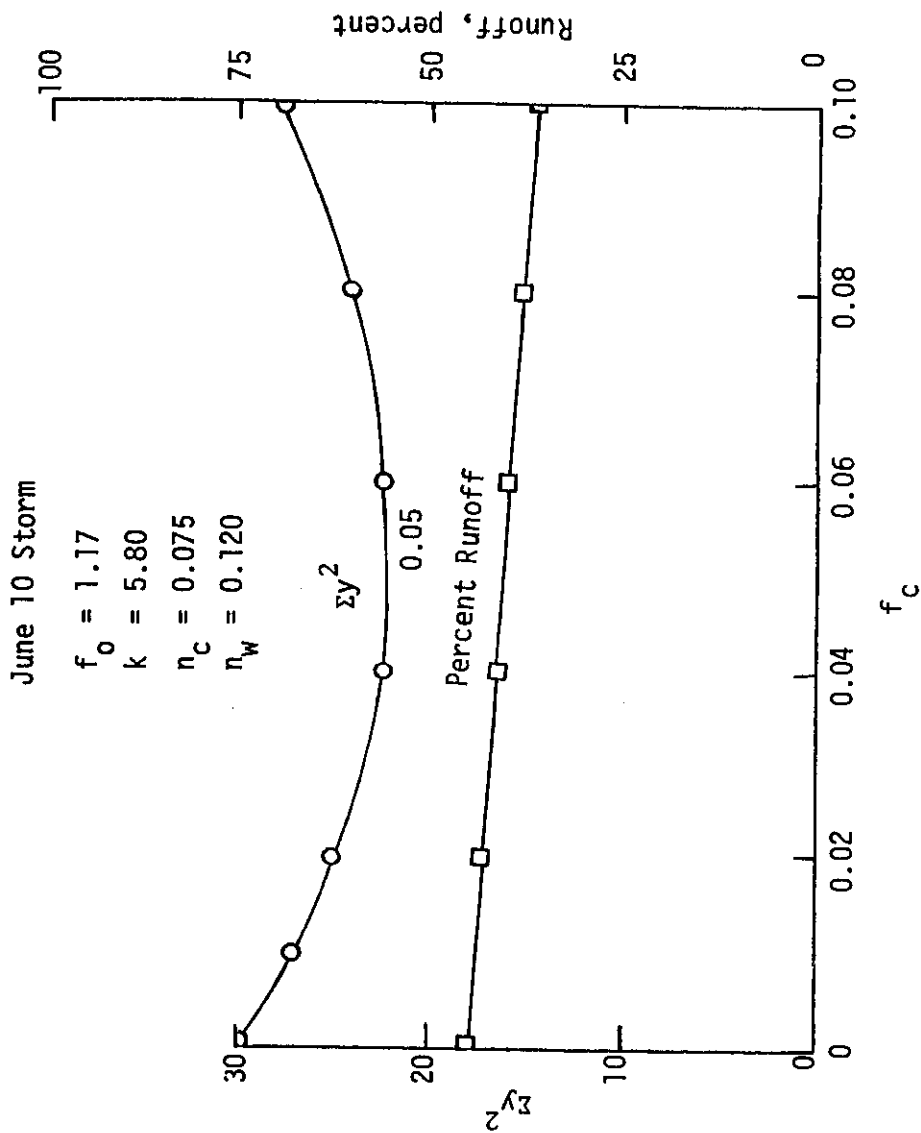


Fig. 5.5. Optimization of f_c and the qualitative effect of f_c on the amount of runoff. (First cycle of optimization process.)

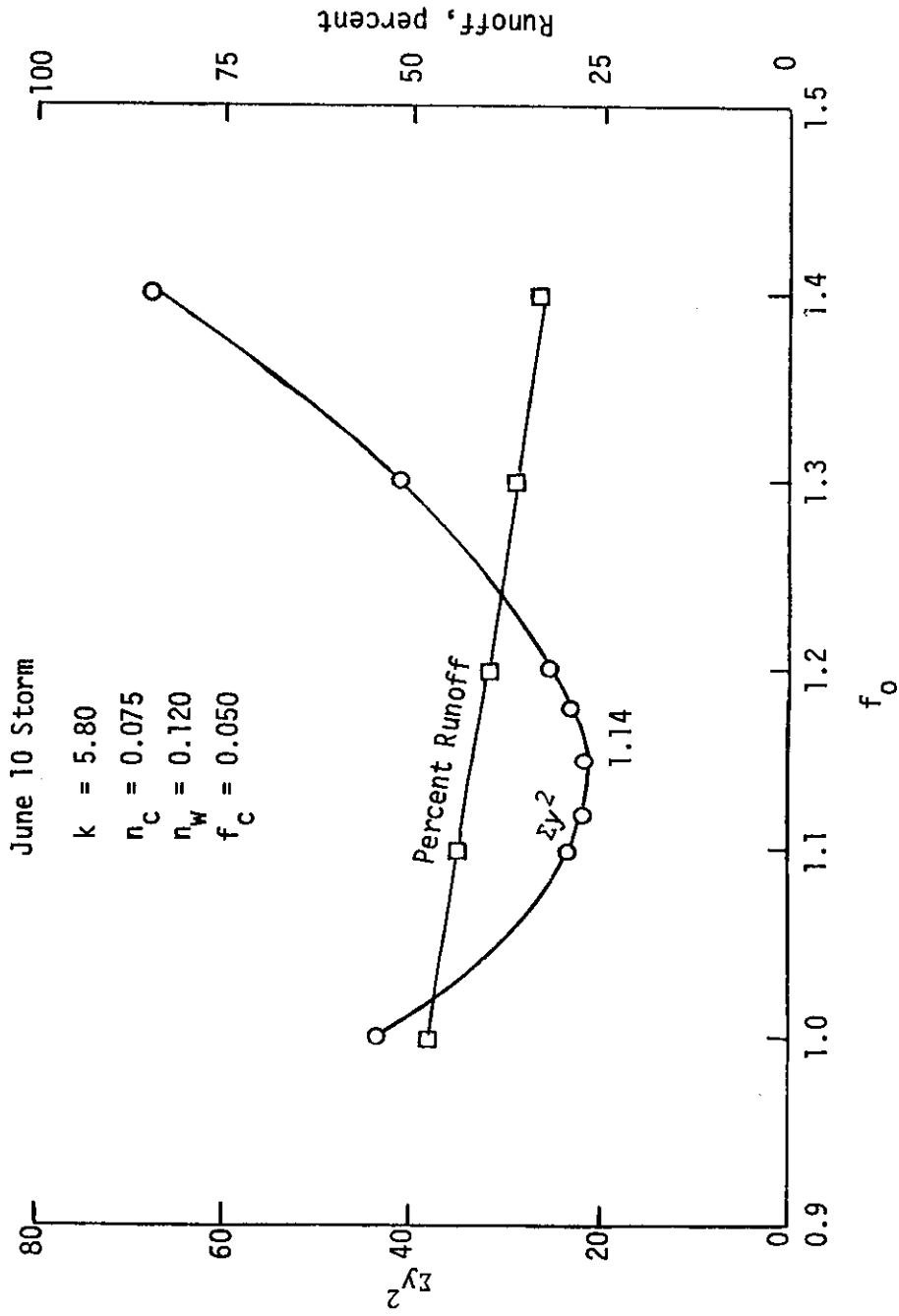


Fig. 5.6. Optimization of f_o and the qualitative effect of f_o on the amount of runoff. (Second cycle of optimization process.)

Figs. 5.1 through 5.5 show that, of the five parameters considered, the initial infiltration rate f_0 has greatest effect on percent runoff. A slight time shift of the runoff hydrograph causes large changes in the computed values on n_c and n_w . Therefore, for research of this type, runoff and rainfall recorders should be carefully synchronized and readable to within 1 min. Fortunately, the values of the Manning roughness parameters have a small effect on runoff amounts as shown in Figs. 5.3 and 5.4.

Rainfall histograms and calculated and measured hydrographs for the two storms are shown in Figs. 5.7 and 5.8. Calculated times to peak flow and values of peak flow were reasonable.

The estimated effect of drying time on the value of f_0 for the two storms and for groups of field data are shown in Fig. 5.9. The value of f_0 increases rapidly with drying time.

Effects of Catchment Geometry

Hydrographs were generated for various catchment widths, lengths, side slopes, and channel slopes. The effects of catchment side slopes and widths are shown in Fig. 5.10 through 5.12. Increasing catchment widths from 10 ft (Fig. 5.10) to 25 ft (Fig. 5.12) had no noticeable effect on percent runoff. Percent runoff increased rapidly with increasing side slopes to a slope of about 0.1 for all three catchment widths. At side slopes greater than 0.1, the effect of increasing slope on percent runoff was less.

During the time this report was being written M. Hollick (14) sent several Australian publications (2,9,31) which describe "roaded" catchments which are similar to the catchments described in this report. Side

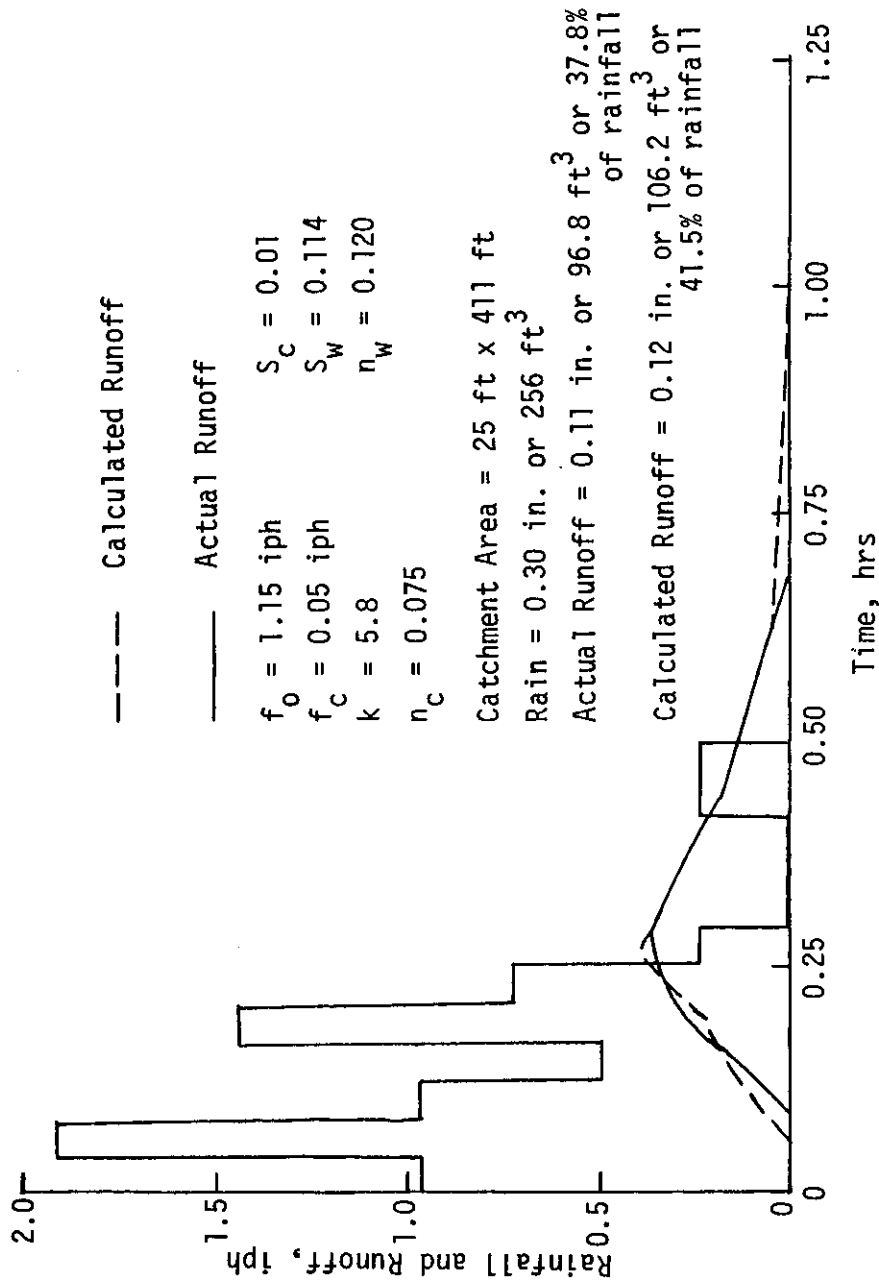


Fig. 5.7. Rainfall histogram and calculated and measured hydrographs for the storm of June 10.

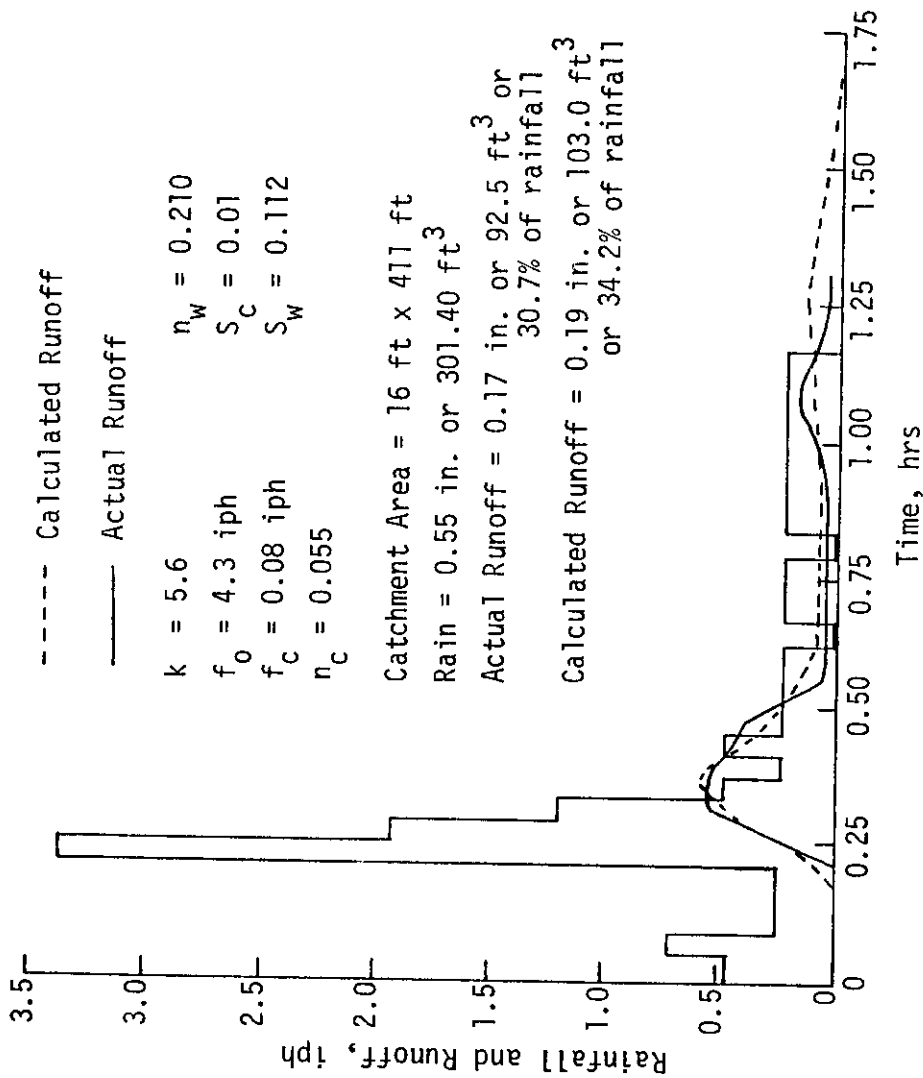


Fig. 5.8. Rainfall histogram and calculated and measured hydrographs for the storm of May 28.

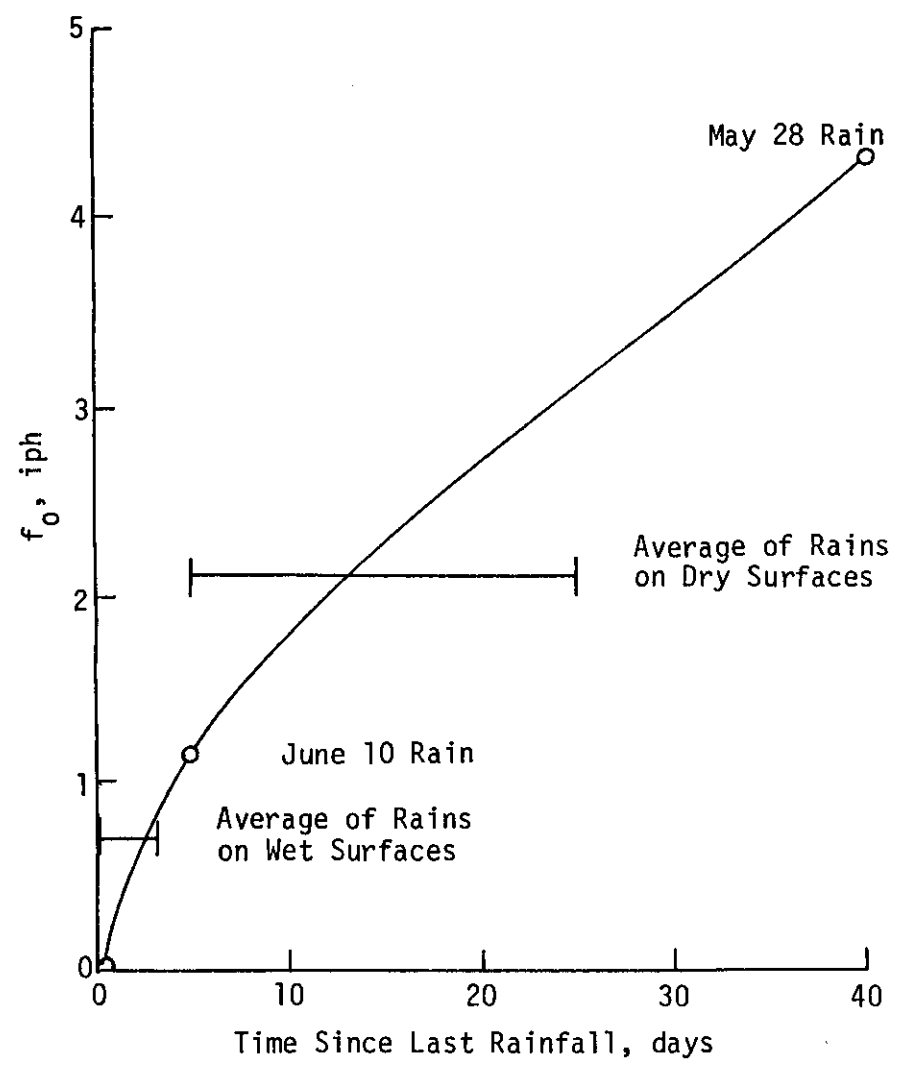


Fig. 5.9. The effect of drying time on initial infiltration rate, f_0 .

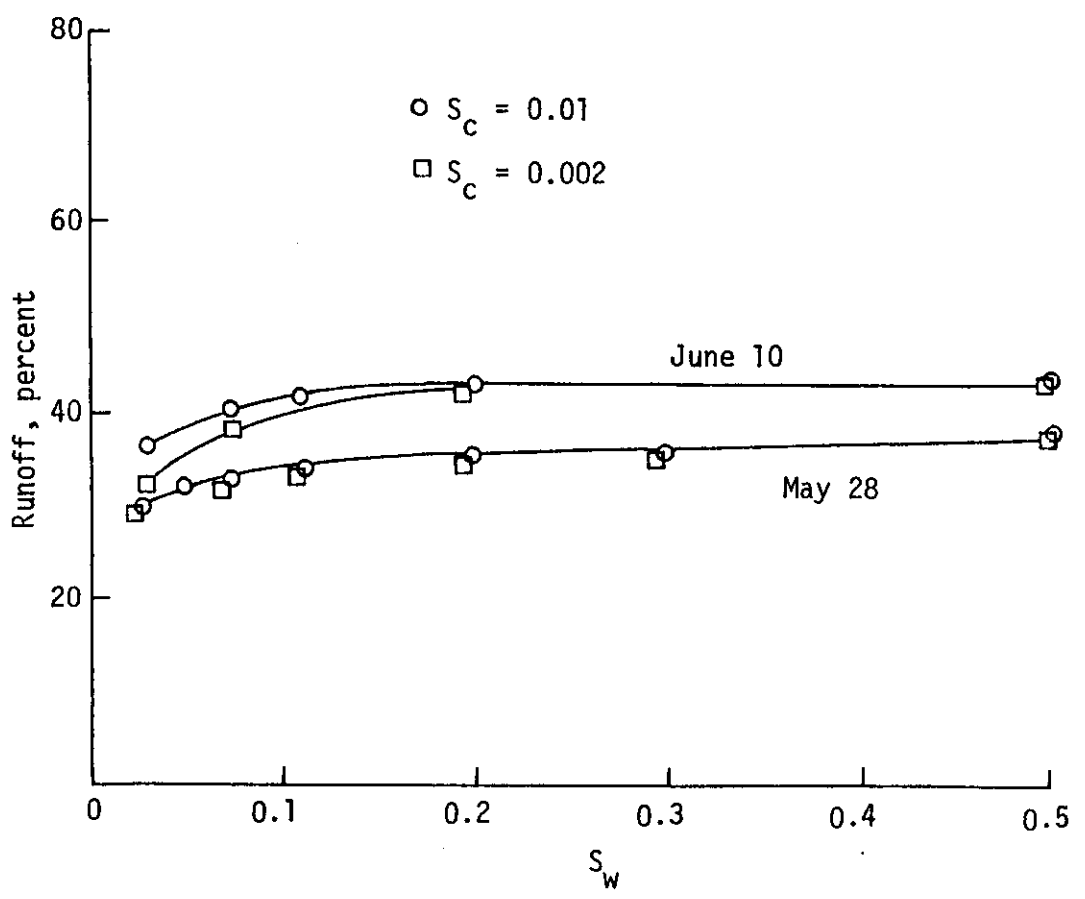


Fig. 5.10. Effect of overland flow slope on the amount of runoff from a 10-ft wide catchment.

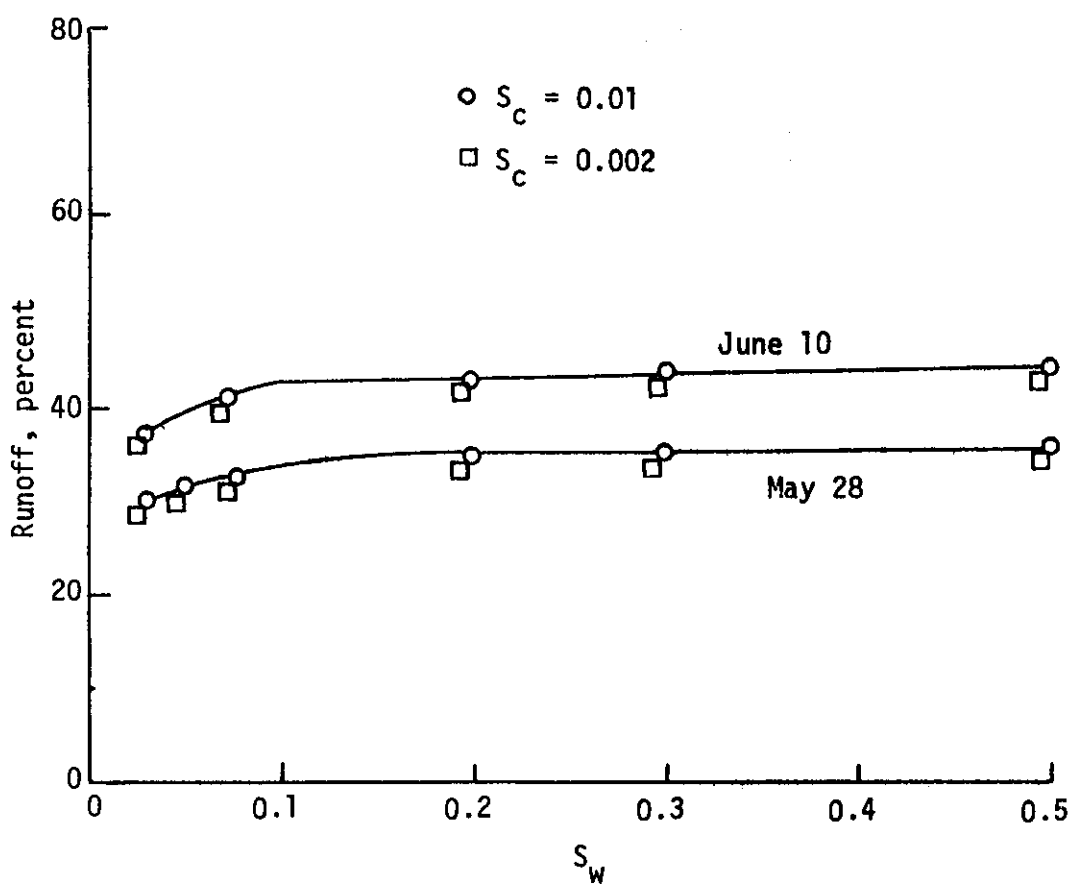


Fig. 5.11. Effect of overland flow slope on the amount of runoff from a 16-ft wide catchment.

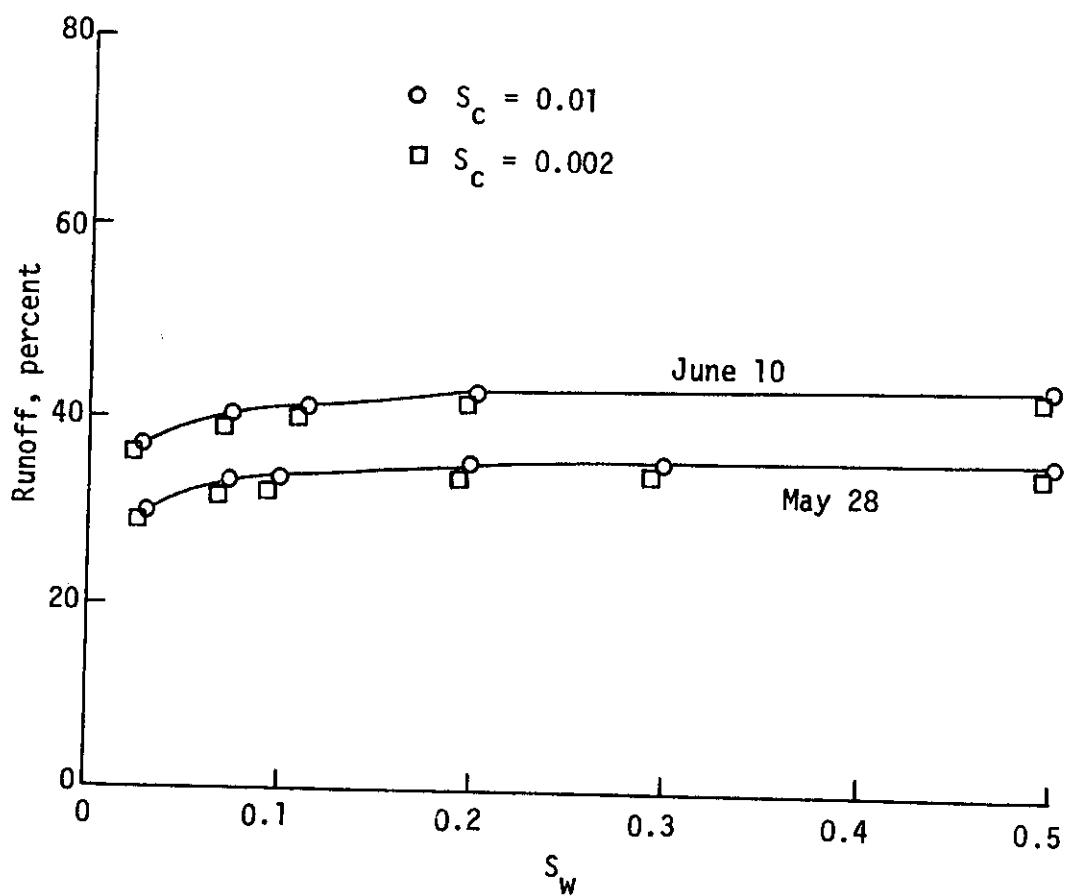


Fig. 5.12. Effect of overland flow slope on the amount of runoff from a 25-ft wide catchment.

slopes between 0.05 and 0.1 were considered optimum for the Australian roaded catchments.

The effects of channel slope S_c , side slope S_w , and catchment length for the two storms are shown in Figs. 5.13 and 5.14. Effects of catchment geometry were similar for the two storms. For flat side slopes ($S_w = 0.03$), percent runoff decreases markedly with increasing catchment length and with decreasing channel slope. At catchment side slopes of 0.2 or more, catchment length and channel slope have a very limited effect on percent runoff within the range of values shown. Significant erosion of Australian catchments occurred with channel slopes of 1 percent (2). Channel slopes of 0.25 percent are recommended in Australia (2).

Summary

Parameter values were acceptable after one optimization cycle. The initial infiltration rate f_0 (Figs. 5.1 and 5.6) had the greatest effect on percent runoff. Therefore, increasing the compaction of the surface should be the best way to increase the percent runoff. The calculated effects of catchment geometry are presented. The results are consistent with Australian field experience. Both indicate that side slopes should be about 0.1 and channel slopes should be about 0.0025. With this catchment shape, catchments up to 25 ft wide and up to 400 ft long can be utilized without loss of much runoff potential.

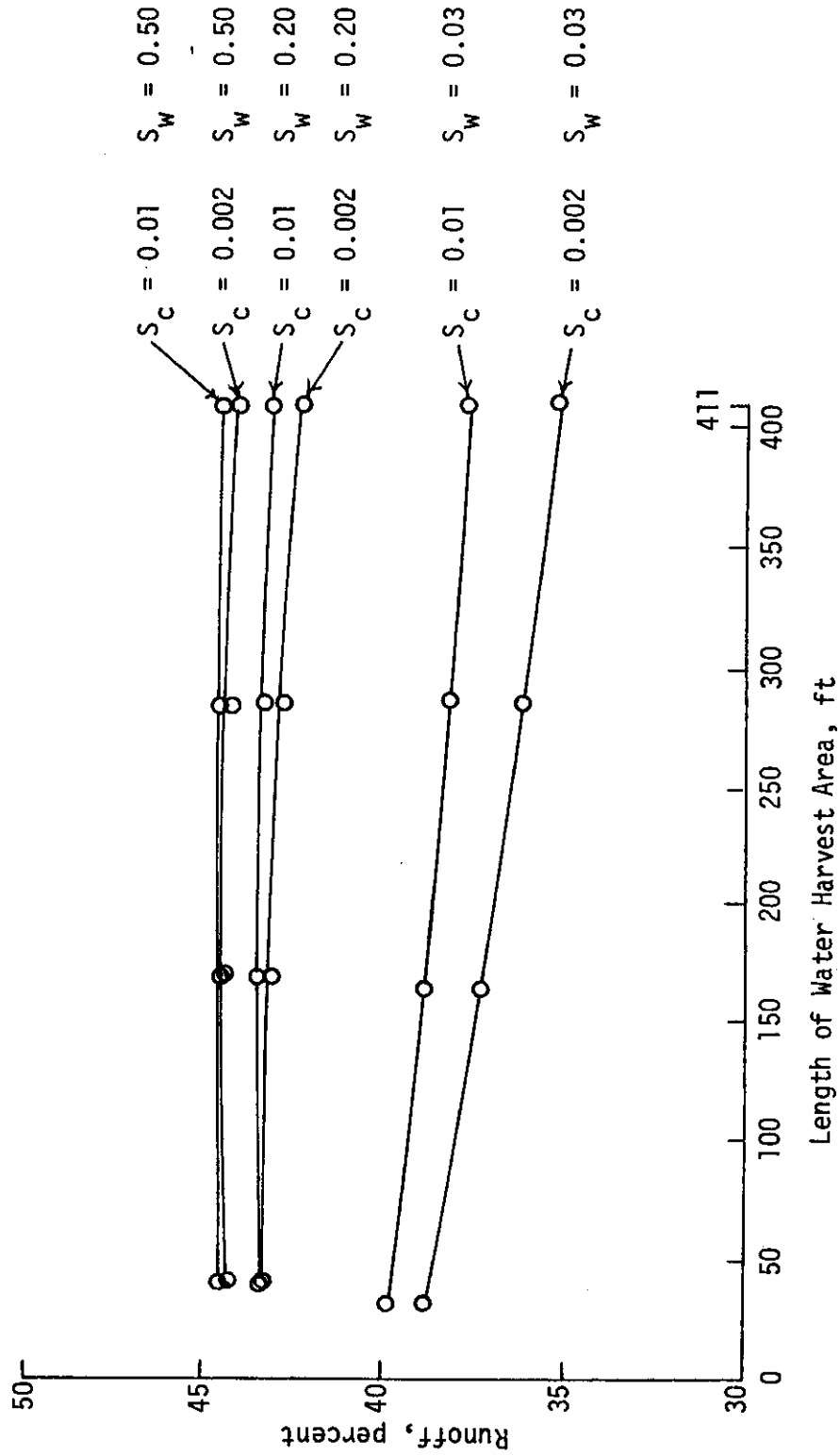


Fig. 5.13. Effect of catchment length and slopes on the amount of runoff from a 25-ft wide catchment for the rain of June 10.

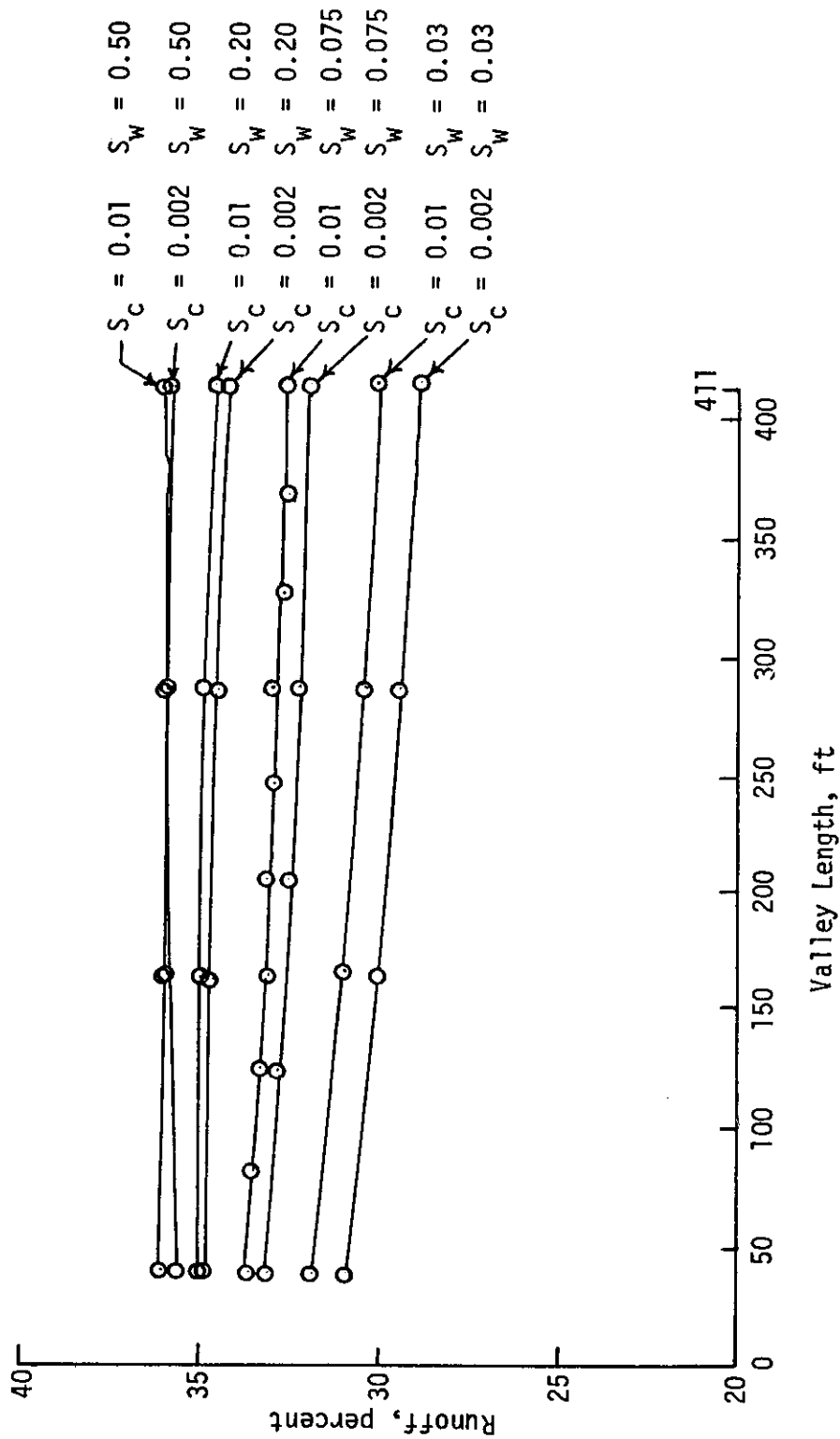


Fig. 5.14. Effect of catchment length and slopes on the amount of runoff from a 25-ft wide catchment for the rain of May 28.

CHAPTER 6

STORAGE OF HARVESTED WATER

Introduction

For the efficient use of the water, any natural or induced runoff may need to be stored until it is needed. Water can be recharged to an aquifer or stored in reservoirs. Two recharge experiments are described in this chapter. Also, a procedure for modifying shallow playa lakes to reduce evaporation from surface storage is proposed.

A Pit Recharge Experiment

All water harvested from field catchments was collected in a 0.1 ac pit. The topsoil was removed to expose the more permeable caliche. Recharge rates were observed during four recharge events and are shown in Fig. 6.1. Recharge rates increase as the depth of water in the pit increases. This fact supports the contention that recharge is restricted primarily by the sediment layer which has accumulated on the pit bottom, and that flow through this layer is governed by Darcy's law and that periodic cleaning of pit may restore original recharge rates. The recharge rates shown in Fig. 6.1 should permit successful recharge of more than 80 percent of the collected water. Two gal of a nonionic wetting agent were applied to the 5000 sq ft pit bottom. The wetting agent did not improve infiltration.

A Water Spreading Experiment

A 1-ft high dike was constructed around a square 1/3-acre plot. The dike was constructed with a tractor-mounted bordering disk. Well water

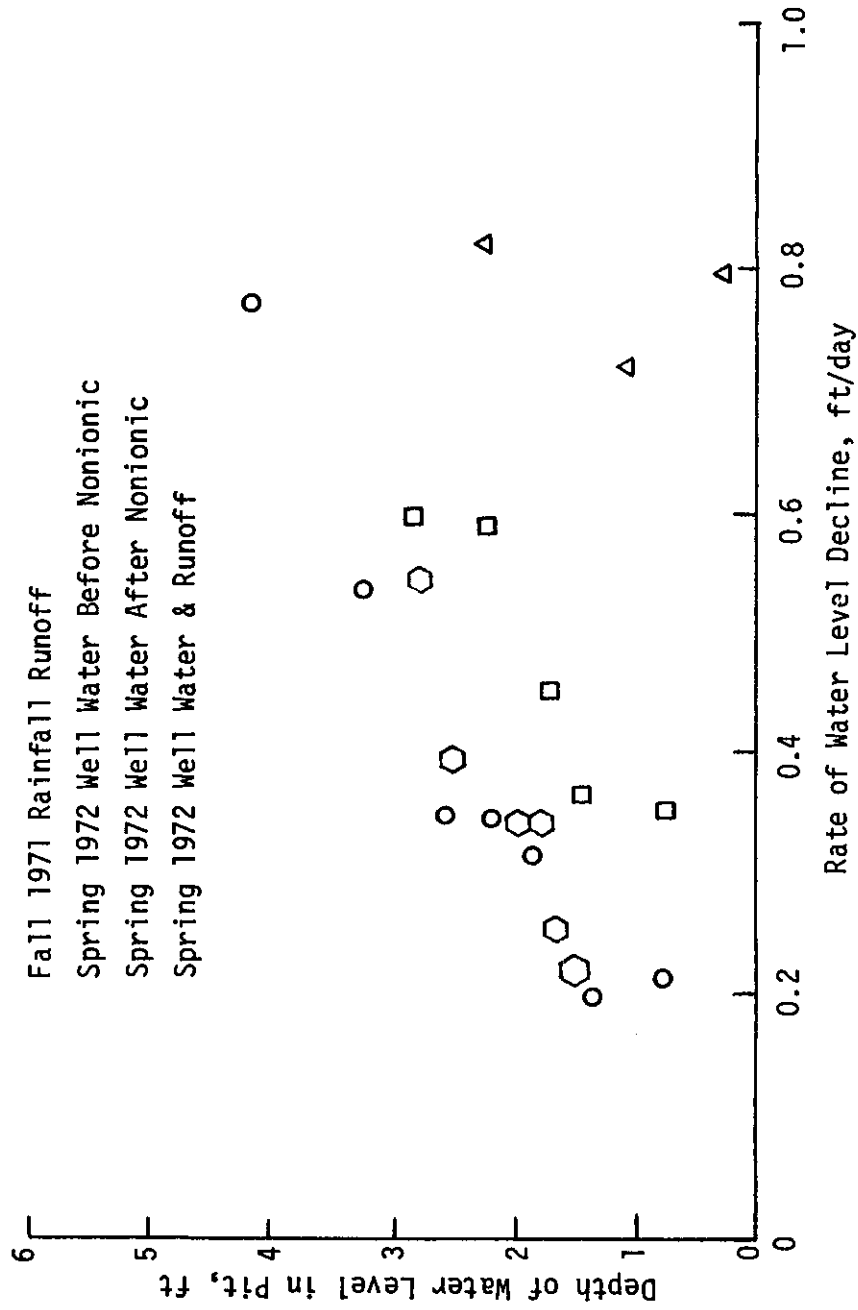


Fig. 6.1. Relationship between water depths and pit recharge rates for 4 recharge events including events immediately before and after the application of 2 gal of a nonionic wetting agent to the 5000 sq ft pit bottom.

was pumped into the diked area periodically to keep the soil surface covered with water. The soil at that site is an Amarillo loam. Infiltration was a relatively constant 8 in. per day for the duration of a 7-day test. Muckel (21) reported that incorporation of 6 in. of cotton gin trash increased the infiltration rate of runoff water into a fine sandy loam soil and increased the length of time before infiltration rates declined.

If the infiltration rate observed could be maintained with runoff water, than water spreading may be a practical method of recharging runoff water where soils are as permeable as the Amarillo loam.

Plausible Economics of Playa Modification

The playa lakes on the Texas High Plains are shallow intermittent lakes. Most of the water which collects in them is lost by evaporation. Modification of playas to reduce evaporation losses may be one means of creating storage for natural or induced runoff.

Estimates of storm runoff to playa lakes on the Texas High Plains range from 365,000 ac-ft per yr (11) to 3,000,000 ac-ft per yr (6). The size and distribution of playa lakes were estimated by Grubbs and Parks (11). These data are reproduced in Table 6.1. Playas are expected to catch an average of at least one full volume per year (11). According to the more conservative estimate, all playas of ten or more acres in size should collect a minimum average total of 340,000 ac-ft per yr.

One method of modifying playas to reduce evaporative losses of water is to dig a circular pit in the playa and use the soil removed from the pit to form a circular dike around the pit. Advantages of this method

Table 6.1. Estimated volume of unmodified playa lakes of the study area when lakes are full. (After Grubbs and Parks (11)).

Area	Size in Acres					Area Total			
	0-4.99	5-9.99	10-14.99	15-19.99	20-29.99		30-39.99	40-49.99	50.
	(acre feet)								
North	574	1,676	2,445	2,294	3,010	342	2,550	29,702	42,593
Central	2,269	9,101	13,221	17,649	34,344	35,635	31,134	128,483	273,836
South	<u>3,312</u>	<u>9,347</u>	<u>11,059</u>	<u>7,550</u>	<u>8,579</u>	<u>4,318</u>	<u>1,911</u>	<u>2,617</u>	<u>48,693</u>
High Plains Total	6,155	20,124	26,725	27,493	45,933	42,295	35,595	160,802	365,122

are the ratio of storage volume to the volume of soil moved would be high, much of the silt could precipitate in the playa before the water is pumped into the storage pit, costs for pumping water up into the pit would not be wasted because the water will need to be pumped to the irrigation system at a higher elevation, and the lake-bottom clay used to form the dikes should prevent excessive seepage losses.

Estimates of storage construction costs shown in Fig. 6.2 are based on the following dike design assumptions:

2:1 side slopes

Top Width, ft = $2\sqrt{\text{Height} + 3}$

Freeboard, ft = Wave Height + 2

Wave Height = $0.025\sqrt{\text{Pit Diameter}}$

4 ft of evaporation + seepage between catchment and usage

27¢/yd earth moval cost

No cut/fill correction

Pit bottom is a conical frustum 10 ft deep and having 2:1 side slopes

If, after initial settling, the playa water contains an average of 225 ppm sediments by weight and 200 ppm settles in the pit, and if the pit is filled once per yr, and if the bulk density of the sediments is >1.0 gm/cc, then the annual sediments will occupy less than 1/5000 of the pit volume. Thus wave erosion will probably be the primary cause of any silt problems.

An estimate of the value of modified playas for storage of natural or induced runoff is indicated by Table 6.2.

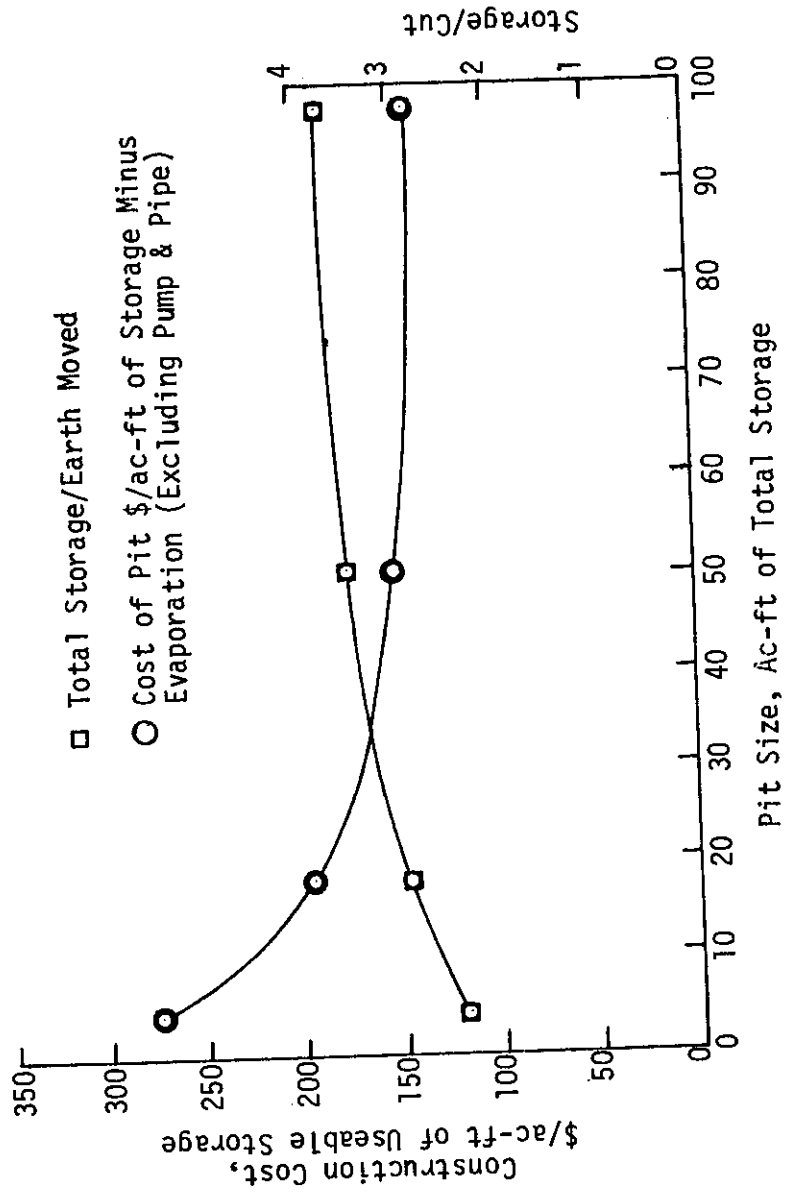


Fig. 6.2. Effect of pit size on the cost of modifying playa lakes for water storage.

Table 6.2. Total predicted 10-year net income from modified playas (\$ per ac-ft of useful capacity).

Annual Added Return From H ₂ O \$/ac-ft (income-operating) ^{a/}	Initial Cost \$/ac-ft of useful capacity ^{b/}					
	130	140	150	170	200	250
5	-208	-238	-274	-294	-360	-468
10	-135	-165	-201	-221	-287	-395
20	10	-20	-56	-76	-142	-250
30	155	125	89	69	3	-105
40	300	270	234	214	148	40
50	445	415	379	359	293	185
70	735	705	669	649	583	475
100	1170	1140	1104	1084	1018	910

^{a/} Operating expense include costs of pumping the water into the pit, costs of distributing water to crops, and costs of water harvest catchments if harvested water is used.

^{b/} Total pit costs are computed from initial cost plus 8 percent compound interest for 10 years. Net income received prior to the end of the 10-year period also earned 8 percent compound interest.

Conclusions

The two recharge experiments which were conducted suggest that both pit recharge and water spreading may be feasible means of transferring runoff to an aquifer for storage. Pit recharge rates increase with increasing water depth in the pit.

Playa modification by the method suggested deserves research attention.

CHAPTER 7

ECONOMIC ANALYSIS

Introduction

Costs for harvesting water include not only the cost of preparing and maintaining the catchments, but also costs of storing the water and lost income from the area used for water harvesting. The costs shown below are estimates based on limited observations.

Construction Costs

As previously noted, catchments were prepared using a road grader, a water truck, and a rubber-tired roller. The construction of adjacent catchments of various widths and side slopes for research purposes required more machine time than would be required for commercial catchments. Therefore, the grader time required to construct the basic catchment shape and to wet and compact the surfaces was observed for several catchments. These data are presented in Table 7.1.

Table 7.1. Grader times and costs for constructing water harvesting catchments.

Catchment Width	Side Slope	Grader		Cost \$/ac
		Time hrs/ac	Rate ^{a/} \$/hr	
16	.11	1.66	15	24.83
24	.11	1.84	15	27.65
32	.08	2.21	15	33.11

^{a/} Rate includes operator.

The grading costs given in Table 7.1 are high because a nearby road embankment made turning impossible and the grader had to back up 400 ft after each pass. However, the data indicate that grading costs will increase as catchment width is increased.

The water truck, which costs \$6 per hr, with operator, was in operation 4 hrs for the construction of 2.5 ac of catchments. Therefore, the watering cost was \$9.60 per ac.

The packer was operated 11.5 hrs or 4.6 hrs per ac. The Western Australian Department of Agriculture recommends surfaces be compacted for 1.5 hrs per ac. At 3 hrs per ac, compaction costs would be \$22.50 per ac.

Thus for 16-ft wide catchments the construction cost (1970) should be \$57 per ac or less.

Maintenance Costs

The primary maintenance cost will be for weed control. Weeds trap wind-blown sediments which trap rainfall. Because the catchment surface cannot be plowed, weeds need to be controlled with chemicals. The chemicals required will depend on the kinds of weeds which become established on the surface.

No herbicides were applied when the field catchments were constructed. Weeds, especially grasses, germinated and emerged readily from the compacted surfaces.

Atrazine applied by spraying at the rate of 4 lb per ac controlled most weeds. Cost was \$11.50 per ac including the application. Dr. D. T. Smith (33) suggested that future catchments installed on the Texas High

Plains could be treated with 2 lb/ac of atrazine (AAtrex) and 1 qt/ac of trifluralin (Treflan) with disk incorporation prior to the compaction of the surfaces. This treatment would cost about \$12.00 per ac including application and should give excellent season-long control of annual grasses and broadleaves. However, this treatment would not control perennial weeds such as johnsongrass and Texas blueweed. Based on field runoff research at Lubbock and Bushland, there is no hazard of atrazine and trifluralin contaminating runoff water (33).

Estimated Water Cost

Net income lost from the area used for water harvesting will vary greatly with previous land use. With the various assumptions noted, costs of harvested water are indicated in Table 7.2.

If the costs in Table 7.2 are substantiated by experience and if the water can be recovered from the aquifer at costs similar to current pumping costs, then water harvesting may be a practical means of supplying water for limited irrigation of cotton and for irrigation of high-value vegetable and fruit crops. Newman (29) has reported yield increase of over 100 lbs of lint per ac-in. of applied water by applying a 2-in. irrigation to cotton at the peak bloom stage of growth. The current price of similar lint is about 20 cents per lb.

The cost of water stored in surface reservoirs will vary with reservoir size and the amount of evaporation between storage and use as shown in Chapter 6.

Table 7.2. Estimated costs of harvesting and recharging water, Texas High Plains.

Investment Costs:	
Harvesting Surface	\$ 55 per harvesting acre
Recharge Pit @ 1¢ per cu ft ^{a/}	<u>110</u> per harvesting acre
Total	\$165 per harvesting acre
Annual Cost:	
Lost Dryland Net Income ^{b/}	\$ 9.03 per harvesting acre
Weed Control and Maintenance	15.00 per harvesting acre
Principal (20 equal annual payments)	8.25 per harvesting acre
Interest (8%, first year)	<u>13.20</u> per harvesting acre
Total	\$45.48 per harvesting acre
Cost per ac-in. (18 in. annual rain-fall):	
35 percent harvested; 90 percent recharged	\$8.02
50 percent harvested; 90 percent recharged	\$5.61

^{a/} Cost for a pit capable of holding 3 in. of runoff.

^{b/} See Osborne, Moore, and Ethridge (30), Table 4.2.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

Laboratory evaluations of water harvesting surfaces have limited field applicability.

By six months to one yr after application, 750 gal per ac of crude oil had no apparent effect on runoff from field plots.

Water harvesting catchments constructed by grading the soil to form V-shaped valleys and then compacting the surface yielded runoff equal to 31 to 43 percent of all precipitation. After rains, sand blown from such catchments may damage tender downwind vegetation. Some water erosion occurred, but, after two years, the basic shape and the performance of the catchments had not been damaged by erosion. Chemical weed control is recommended.

Hydrographs were successfully modeled by the kinematic wave method. Hydrologic parameters were estimated by a univariate procedure. The initial infiltration of the soil surface had the greatest effect on the amount of runoff. Thus, additional or repeated compaction may be the best practice for increasing runoff from such surfaces. Surface roughness had little effect on the amount of runoff.

After studying field data, computer generated hydrographs, and published accounts of Australian experience with similar catchments (2,9, 31), the writers recommend the following design criteria for water harvesting catchments on the Texas High Plains.

Catchments should be as narrow as can be constructed easily with conventional equipment. A catchment width of 16 ft may be about optimum.

Catchment side slopes should be between 0.1 and 0.2. Generally, catchments should be no more than 1/8 mi long. With these side slopes and lengths, channel slopes can be as little as 0.002 without causing excessive loss of runoff. To prevent erosion, channel slopes should not exceed 0.005. Catchment surfaces should be wetted by rain or by sprinkling before rolling. Surfaces should be rolled with a rubber-tired roller for 1.5 to 3 hrs per ac. Drop structures should be installed at elevation changes to prevent erosion.

Carder (2) recommends that soils used for catchments contain no less than 3 percent clay, and the gravel retained on a 3/16 in. screen should not exceed 25 percent. Most Texas High Plains locations fit this criterion. In sandy areas, wind-blown sand may fill the valleys and render them ineffective.

The cost of constructing graded catchments should be \$55 per ac or less. If water is not available from other sources, harvesting of water from graded or "roaded" catchments is an economically feasible means of obtaining water for livestock, homesteads, and small municipalities. On the Texas High Plains, the use of harvested water for limited irrigation of cotton or high-value fruits may be feasible, depending on the situation. The cost of harvested water is expected to be about \$8.00 per ac-in. Efficiently-utilized natural runoff should be less expensive water.

REFERENCES

1. Burman, R. D. and R. D. Black. 1970. The inference of intake and hydraulic roughness parameters from plot runoff using kinematic wave theory. *Trans. of the ASAE.* 13(4):479-481.
2. Carder, D. J. 1970. Roaded catchments: A method of increasing run-off into dams and reservoirs. Western Australian Department of Agriculture. Technical Bulletin No. 5.
3. Cluff, C. B. 1967. Water harvesting plan for livestock or home. *Progressive Agriculture in Arizona.* XIX(3):6-8.
4. Cluff, C. B. and G. R. Dutt. 1966. Using salt to increase irrigation water. *Progressive Agriculture in Arizona.* XVIII(3):12-13.
5. Cluff, C. B., G. R. Dutt, M. M. Fogel and L. G. Wilson. 1969. Development and evaluation of water harvesting systems. Project Completion Report. OWRR Project No. A-001-ARIZ.
6. Dvoracek, Marvin J. and Rolland Z. Wheaton. 1969. Development of systems for ground water recharge into the Ogallala formation. Texas Technological College. Special Report No. 23.
7. Evenari, M., L. Shanan and N. H. Tadmor. 1968. Runoff farming in the desert. I. Experimental layout. *Agron. Jour.* 60:29-32.
8. Evenari, M., L. Shanan, N. Tadmor and Y. Aharoni. 1961. Ancient agriculture in the Negev. *Science* 133, 3457:979-996.
9. Firth, J. L. and R. A. Nulsen. 1971. Clay cover for roaded catchments. Western Australian Department of Agriculture. Bulletin No. 3824.
10. Geddes, H. J. 1962. Water harvesting. CSIRO Conference on Water. Canberra, Australia.
11. Grubb, Herbert W. and Don L. Parks. 1968. Multipurpose benefits and costs of modifying playa lakes of the Texas High Plains. Texas Technological College. Special Report No. 6.
12. Henderson, F. M. and R. A. Wooding. 1964. Overland flow and ground water flow from a steady rainfall of finite duration. *Jour. of Geophy. Res.* Vol. 69(8):1531-1539.
13. Hill, Leon W. 1968. Address to the Thirteenth Annual Water for Texas Conference. College Station, Texas.
14. Hollick, M. 1972. Personal correspondence.

15. Kemper, W. D. 1966. Personal communication.
16. Lauritzen, C. W. 1968. Flexible membranes for water applications. World Irrigation.
17. Lauritzen, C. W. 1967. Rain traps of steel. Utah Science 28(3).
18. Lauritzen, C. W. and A. A. Thayer. 1966. Rain traps for intercepting and storing water for livestock. Utah Agricultural Experiment Station. ARS-USDA. Bulletin No. 307.
19. Liggett, James A. and D. A. Woolhiser. 1967. Difference solutions of shallow water equation. Jour. of Engineering Mechanics Division. ASCE. 93:39-71.
20. Linsley, R. K., M. S. Kohler and J. L. H. Paulhus. 1958. Hydrology for Engineers. McGraw-Hill Book Company, Inc. New York. 340 p.
21. Muckel, Dean C. 1959. Replenishment of ground water supplies by artificial means. ARS-USDA Technical Bulletin No. 1195.
22. Myers, L. E. 1960. Chemicals for water conservation. Paper presented before Fourteenth Annual Nevada Water Conference, Carson City, Nevada.
23. Myers, L. E. 1964. Harvesting precipitation. International Association of Scientific Hydrology. Publication No. 65. Berkeley, California.
24. Myers, L. E. 1967. Recent advances in water harvesting. Jour. of Soil and Water Conservation, SCSA. 22(3).
25. Myers, L. E. 1965. Water harvesting with plastic films. Paper presented at Sixth National Agricultural Plastics Conference. Phoenix, Arizona.
26. Myers, L. E. 1961. Waterproofing soil to collect precipitation. Jour. of Soil and Water Conservation. 16(6):281-282.
27. Myers, Lloyd E., G. W. Frasier and J. R. Griggs. 1967. Sprayed asphalt pavements for water harvesting. Jour. of Irrigation and Drainage Division, ASCE. 93(3):79-97.
28. New, Leon. 1972. 1971 High Plains irrigation survey. Texas A&M University Agricultural Extension Service.
29. Newman, J. S. 1967. Irrigation water management. 1965-1966 Report of Progress. South Plains Research and Extension Center, Texas Agricultural Experiment Station, Texas A&M University.

30. Osborne, James E., Donald S. Moore and Don E. Ethridge. 1969. Expected production requirements, costs and returns for major crops--medium-textured soils--Texas High Plains. Texas Agricultural Experiment Station, Texas A&M University. MP 922.
31. Public Works Department of Western Australia. 1956. Roaded catchments for farm water supplies. Bulletin No. 2393.
32. Richardson, C. W., R. W. Baird and E. T. Smerdon. 1968. Computer methods for predicting storm hydrographs based on antecedent soil moisture. Paper presented at the 1968 Annual Meeting of the American Society of Agricultural Engineers. Logan, Utah.
33. Smith, D. T. 1972. Personal correspondence.
34. Wei, J. P. 1966. Overland flow hydrograph synthesis by digital computer. MS thesis. Agricultural Engineering Department, Texas A&M University.
35. Woolhiser, D. A. 1972. Personal communication.