SIMULATION OF WATER RELIABILITY ON A SMALL-SCALE WATER HARVESTING AGRISYSTEM

by

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TABLE OF CONTENTS

TABLE OF CONTENTS--Continued

LIST OF ILLUSTRATIONS

LIST OF TABLES

ABSTRACT

Water harvesting techniques are being studied to determine its potential as an alternative reclamation practice. To assist planners and decision makers in evaluating the water harvesting potential, a procedure is developed by which precipitation and its distribution are simulated and incorporated with a runoff model to forecast the long term availability of harvested water.

The output from the stochastic precipitation model and statistically-derived runoff model provide a simulated 100 years of annual precipitation and runoff events. Two reservoirs were designed and evaluated separately using varied seasonal irrigation demands. The sensitivity analysis, of varying the demand, revealed yearly water reliability decreased as the total seasonal irrigation demand approached the mean annual runoff. It was also shown that an appropriate reservoir size could be chosen using the probability distributions of the number of dry reservoir days and the number of days the reservoir overflows.

INTRODUCTION

Disturbed land reclamation is of significant importance throughout the United States and is becoming an increasingly critical issue in the desert southwest. Growing public concern with increased mining activity has focused attention on environmental impacts of mining and abandoned mined land. This concern has led to the establishment of state and federal regulations which describe safeguards and reclamation operations. The Department of the Interior's Federal Register on Surface Coal Mining and Reclamation Operations now directs that areas disturbed by mining practices be restored to the pre-mining productivity. The reclamation procedures include recontouring the overburden to conform with local topographic features, followed by redistribution of temporarily stockpiled topsoil over the recontoured overburden to enhance the revegetation process.

Water harvesting is one means of enhancing productivity of the affected areas beyond their pre-mining levels. Arid land agriculture, historically practiced thousands of years ago by desert inhabitants of the Middle East, was originally made possible through water harvesting. The University of Arizona began in 1978 to study the feasibility of water harvesting as a viable method of reclaiming land altered by strip mining in a project funded by the Bureau of Mines. A prototype water harvesting agrisystem was developed on mine spoils of the Black Mesa in northern Arizona in an effort to develop a reclamation alternative and possibly increase land benefits through small-scale agrisystems.

Traditional observation techniques are far too time consuming for efficient evaluation of water harvesting system performance. Computer modeling can shorten this time dimension by simulating long term precipitation and runoff events.

The objective of this study is to determine for the Black Mesa water harvesting agrisystem, the potential water available on a yearly basis and the reliability of having stored water available during Black Mesa's growing season.

The following steps were taken to meet this objective.

1. Develop a stochastic precipitation model for the study area.
2. Incorporate the rainfall model into a statistically derived runoff model.
3. Develop probability density functions for precipitation per event and interarrival time between events.
4. Develop probability density functions for the number of days during the growing season the reservoir was dry.
5. Develop probability density functions for the number of days that the reservoir overflowed.
6. Determine the effect of varied irrigation demand and reservoir maximum stage on water reliability during the growing season.

The following chapters present this procedure in detail, discuss the study's results, and develop conclusions.

SITE DESCRIPTION

The study site is located on the Black Mesa, near Kayenta, in northeastern Arizona (36.5°N, 110.5°W). The Black Mesa is on the Navajo and Hopi Indian Reservations and the Navajo/Hopi Joint Use area; its location is shown in Figure 1. Grazing by sheep, goats, and cattle is a major land use. An abundance of relatively high grade bituminous coal is found on the Black Mesa, and since 1970, the Peabody Coal Company's surface mining operations have become the region's main industry.

Precipitation on the Black Mesa has a bi-modal summer and winter distribution. Summer precipitation occurs in the form of sporadic higher-energy convectional and frontal convectional storms. These storms, consisting of small diameter cells, are concentrated on and along highlands at altitudes above 7,000 feet and more randomly distributed in lower relief areas. Winter precipitation generally occurs in more evenly distributed storms associated with well defined frontal systems. Storms in this category have lower intensities and higher infiltration, and probably contribute substantially to ground water recharge (Smith, 1978). The average annual precipitation is approximately 10 inches. Although recent precipitation monitoring at the Black Mesa has shown maximum annual values approaching 12 inches, nearby long-term records include extended dry periods, dropping the average to less than 10 inches. A highly variable climate is thus characteristic of the Black Mesa (Fogel, Franklin, and Harwood, 1982).

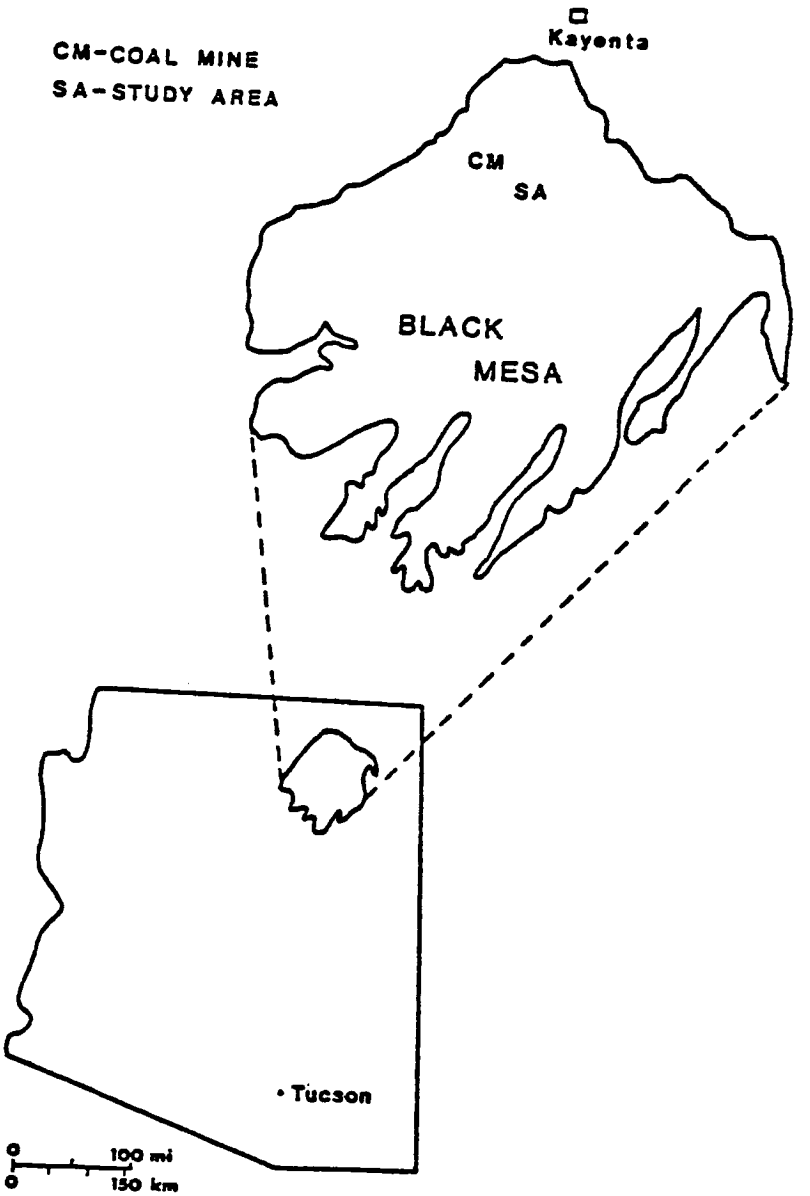

Figure 1. Black Mesa, northeastern Arizona, showing study area location (Fischer, 1976).

The vegetation of the Black Mesa in the vicinity of the study site consists of juniper (*Juniperus osteosperma*) and piñon (*Pinus edulis*) with scattered Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*) in the upper story. Sagebrush-snakeweed in the shrub layer, and blue grama (*Bouteloua gracilis*), Indian rice grass (*Oyrzopsis hymenoides*), and sand dropseed (*Sporobolus cryptandrus*) and clovers in the ground layer (Gummerman, 1970; EH&A, 1980).

The soils in the study area are coarse to medium textured, usually either a sandy loam or sandy clay loam. The overburden deposits, from the mining operations, are poorly developed and contain a high percentage of montmorillinitic clay (Van der Puy, 1979; Fogel et al., 1982).

In 1978, the Bureau of Mines funded a project to evaluate water harvesting techniques as a means of reclaiming land altered by strip mine operations. The water harvesting system, developed by the University of Arizona's School of Renewable Natural Resources, consists of two primary catchments: a 7.5 acre area of fibreglass-asphalt-chipcoat (FAC) membrane and a 5.3 acre area of salt-treated compacted earth. Another area, approximately 5 acres and consisting primarily of roadways, was untreated. The collected water is stored in three small reservoirs. Water can be transferred between reservoirs by either a distribution channel, gravity-feed pipeline, or a pump. Two agricultural terraces were established, each approximately two and one half acreas in area. Water is pumped from the reservoirs to the terraces for irrigation of the various vegetable crops. An additional 1-acre FAC catchment-orchard was designed as a self-supporting system and is described by Van der Puy (1979). Figure 2 shows the design of the Black Mesa Agrisystem.

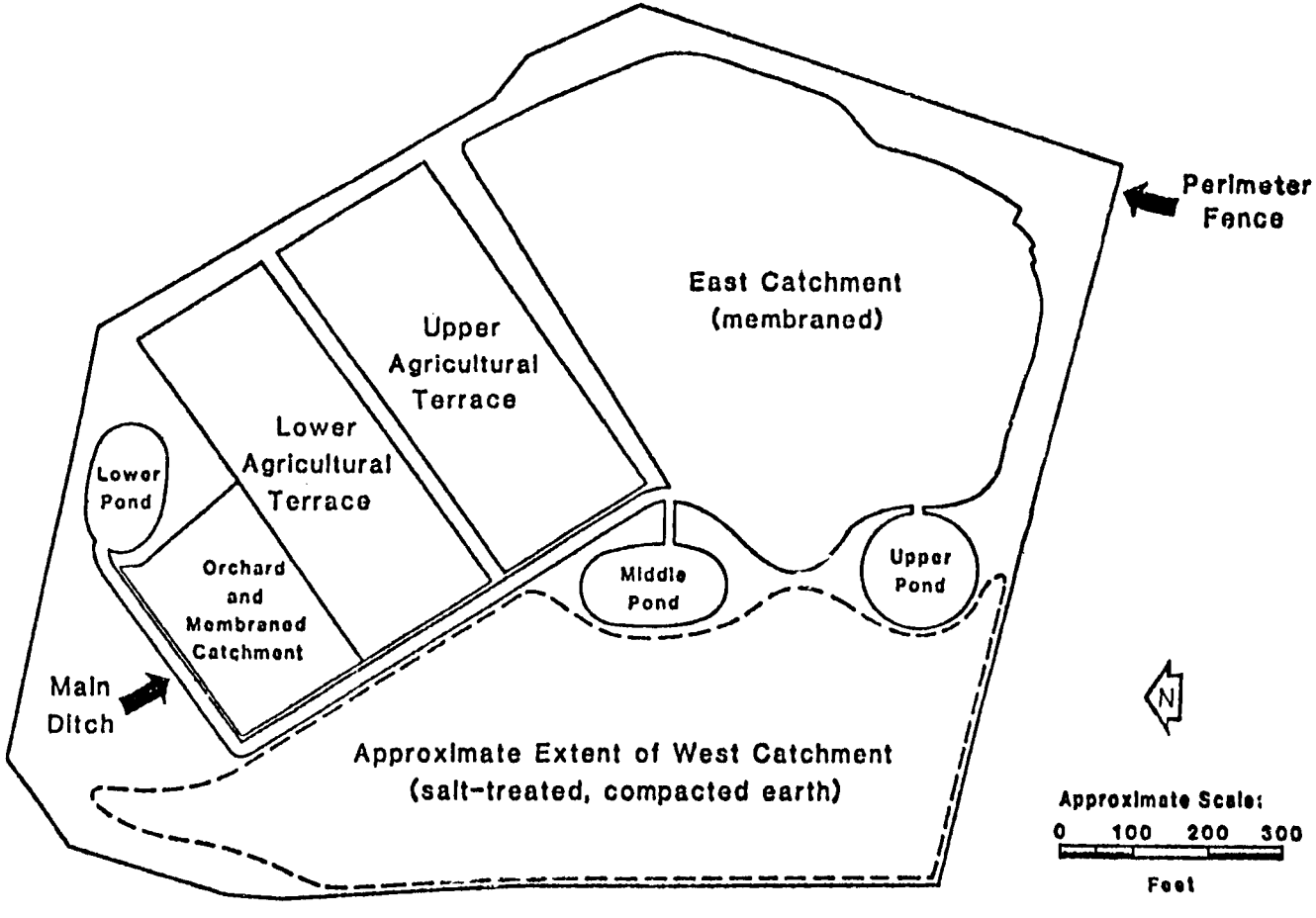

Figure 2. Black Mesa water harvesting agrisystem (Powelson et al., 1980).

Hydrologic instrumentation was installed in the spring of 1981 to monitor the runoff from both the salt-treated and FAC catchments. Runoff was measured using two 1-foot H-flumes. One flume sampled a 0.215 acre sector of the 5.29 acre total salt-treated catchment, and the second sampled a 0.717 acre sector of the 7.53 acre total FAC catchment area. The runoff stage was monitored continuously with type FW1 water level recorders.

LITERATURE REVIEW

Water Harvesting

Water harvesting involves collection and storage of water from precipitation. Harwood (1979) defined water harvesting systems as artificial methods whereby precipitation can be collected and stored until it is beneficially used. The system consists of a catchment made more impervious by artificial means than it was in its natural state and, unless the water is to be immediately used, a storage facility for the harvested water is required. The term was first used by Geddes of the University of Sidney in the 1950's, but the practice dates back approximately 4000 years to the Middle Bronze Civilization. During this period, inhabitants of the Negev Desert cleared hillsides of rock and gravel and smoothed the soil to increase runoff. Contour ditches were dug on hillsides to collect the water and carry it to lower lying fields where it was used to irrigate crops. Although these early runoff systems were not as efficient as some of the current water harvesting practices, they enhanced the development of agricultural civilizations in a region having less than adequate rainfall.

Water harvesting methods are site specific. Before a system is installed, the designers must know: 1) soil characteristics, such as water-holding capacity, inflitration, and erodability; 2) topographic features, such as slope and direction followed by natural runoff; 3) precipitation amount, frequency, and intensity; and 4) the major climatic

variables of wind, solar radiation, temperature, and humidity (National Academy of Sciences, 1974).

Catchment treatments for reducing infiltration and increasing runoff are numerous. Land alteration is an inexpensive and convenient method. With this method, runoff water is collected and conveyed in ditches or rock walls along hillside contours. Runoff efficiency can be improved by removal of rocks and vegetation, followed by soil compaction.

Cooley, Dedrick, and Frasier (1975) discuss the primary water harvesting treatments in two categories: 1) chemical and physical soil treatments; and 2) soil covers. They define chemical and physical soil treatments as the treatment of the soil surfaces with materials to prevent infiltration. Sodium chloride, applied in large quantities, has been found to be effective. It has reasonable durability and apparently does not affect water quality. Other chemical treatments include silicon water repellents and paraffin wax. Selection of chemical treatments depends upon properties of the soil. In contrast, soil cover treatments can generally be applied to a wide range of soil types, since they only use the soil as a supporting structure and do not depend on its properties to provide water repellancy. Asphalt pavements and combinations of asphalt and fiberglass are used on nonswelling soils. Rubber sheeting is a widely used ground cover treatment and has been found to be very durable. The high cost of concrete and its frequent maintenance requirements has limited its use. Reported runoff efficiencies are in the range of 50-90 percent for the chemically treated catchments, and 60-95 percent for covers (Cooley et al., 1975).

Storage is an integral part of any water harvesting system. Optimizing the storage design requires minimizing both seepage and evaporation. Methods to reduce seepage include various chemical treatments, such as application of sodium chloride, and physical methods such as installation of synthetic linings. Considerable experimentation has been conducted on floating covers and suspended fabrics which reduce evaporation losses from the storage reservoir. Long-term field studies have shown evaporation reductions of 60-95 percent (Cooley, 1974).

Precipitation Model

Computer technology has been growing rapidly over the last ten years. Computer usage has infiltrated practically every facet of our lives with phenomenal benefits. Computer programs and models which simulate important hydrologic processes have been developed and used by practitioners and decision makers in the field of water resources. Water resource planners, consultants, researchers, managers, or legislators have all benefited from this tremendous influx of knowledge made available through computer technology.

The University of Arizona has pioneered in the development and use of an event-based stochastic precipitation model that has been validated for a variety of conditions (Fogel, Duckstein, and Sanders, 1971). The model uses a historical precipitation record to develop frequency distributions for two parameters: precipitation per event, and the number of days between events.

The methods of moments is then used to develop representative theoretical distributions. The generated probability density function,

PDF, when integrated goes to unity. Therefore, this cumulative density function, CDF, is increasing from zero to one. The stochastic model generates random numbers within this range and then compares each random number to the theoretical CDF indicating an interval class, for either interarrival time or precipitation per event, associated with the generated random number. An extended precipitation record can be simulated and frequency distributions for this record can be derived.

In many cases winter and summer precipitation characteristics differ and must be modeled separately. Summer storms generally occur as independent events, while winter precipitation often occurs in the form of continuous or intermittent events produced by relatively large scale frontal systems. Duckstein, Fogel, and Davis (1975) consider winter precipitation as events grouped in sequences of days on which a certain minimum precipitation occurs. This overcomes the dependency problem characteristic of winter events, and allows generation of statistically acceptable frequency distributions.

Runoff Model

There are many runoff formulas based on empirical analysis. See, for example, Mostaghimi and Mitchell (1982), and Schwab et al. (1966) for reviews and discussion. Several formulas are used to calculate the volume of runoff for extreme events. Cooks' runoff equation is a function of return period and two other empirical factors. Chow's model computes runoff using a coefficient dependent upon various characteristics of the watershed, the watershed area, and another factor determined from

field observations. The rational method relates peak runoff rates to rainfall intensity, to a coefficient, and to the watershed area. These relatively simple models have had wide application in the United States. The more elaborate SCS runoff equation has perhaps the most widespread application of all the runoff formulas (Rallison, 1980). It was developed by the Soil Conservation Service in the mid 1950's, after more than twenty years of rainfall-runoff study. The formula was originally used for estimating the effects of land treatment and land use changes upon runoff resulting from storm rainfall. Because of its simplicity it soon became a valuable tool having many hydrologic applications. It is now often used to estimate runoff from ungaged watersheds. The watershed curve number and the amount of storm precipitation are the most significant factors in the equation. The curve number, representative of average conditions on a watershed, is determined for a particular combination of soil and cover characteristics, often referred to as the soil-cover complex.

The statistical development of runoff models is another approach. Various correlation analyses; bivariate, partial, multiple, etc., have been successful in determining viable runoff equations. Arnell (1982), used a simple regression analysis of runoff and rainfall volumes to derive a linear equation used in his estimation of runoff volumes from urban areas. These statistically derived runoff models are often site specific, but with high correlation coefficients, they often yield the best estimates.

MODEL FORMULATION

The computer models used in this research, generate an extended precipitation record which can then be transformed into runoff and stored in a reservoir. This can then be used to develop storage-yield relationships. The precipitation model uses the simulation technique developed by Fogel et al. (1971) at the University of Arizona, while runoff is calculated with a model developed from rainfall-runoff relationships measured on two water harvesting catchments.

Precipitation Model

The precipitation model is a simulation technique that uses a limited historical precipitation record to generate extended precipitation records. In this research project, the model provides the first step in compiling long-term potential water supply reliability estimates.

The short term precipitation record for the study site was compared with a long term weather record from the U.S. Weather Bureau Station at Betatakin National Monument to determine compatibility. The Betatakin station, located 15 miles north of the study site, provides a continuous 25 year precipitation record running from 1952 through 1977. The station has an elevation of 7,200 feet compared to 6,600 feet at the study site.

Since the amount of precipitation generally increases with elevation, the Betatakin precipitation data was adjusted downward to provide a better estimate of precipitation for the study area. Each precipitation

event was reduced by a percentage based on the relationship between mean annual precipitation for Betatakin and the mean annual precipitation for the study site. Myhrman (1978) found that value to 12.19 percent.

The precipitation model developed theoretical frequency distributions calculated parameters from the observed data. The program that developed the observed distributions read the data and classified, by months, the interarrival time between events and the amount of precipitation per event. It was assumed that the precipitation which fell on one day was generated by one storm and therefore, the smallest interarrival time was one day (Franklin, 1981). Interarrival times greater than 70 days were infrequent and judged to be insignificant to the results of this study, so an upper limit of 70 interarrival days was selected with the one day class interval. The maximum rainfall event, which was assumed to be 2 inches or less, was broken down into 40 classes at 0.05 inch intervals.

The precipitation per event probability density function, PDF, was computed by dividing the number of events in each class in that month, by the total number of events for the month. The cumulative density function, CDF, by definition, was computed as the cumulative of the PDF.

The interarrival time probability density function was computed by dividing the number of days between events in each class in that month, by the total number of interarrival days for the month. The CDF was also computed.

The Student's T-test of Means was used to statistically compare each month with every other month. The results from the T-test indicated

that the twelve monthly distributions, for both interarrival time and precipitation per event, fell into four separate groups (Tables 1 and 2).

The statistically derived groups would probably differ if the monthly distributions were grouped according to monthly meteorological characteristics. However, the 20 year Betatakin record was considered adequate to group the distributions using a viable statistical test.

Probability and cumulative density functions were derived for each group and values of λ and K were also calculated. Figures 3 and 4 show probability distributions for interarrival time and precipitation per event for grouped months. The parameters, λ, K, and Γ, value of the gamma function, were used to generate theoretical gamma distributions for each of the groups within the event characteristics of interarrival time and precipitation per event.

The probability density function for the gamma distribution is:

$$f_X(X) = \lambda^K X^{K-1} \exp-\lambda X/\Gamma(K) \ , \qquad (1)$$

where K and λ are shape and scale parameters, respectively, and X is the random variable, precipitation per event or the number of interarrival days. The random variable, X, is the range of precipitation per event or the range of interarrival days.

Other theoretical distributions, such as a geometric or exponential, may also have proved to be "good fits." Theoretical distributions shown to fit observed distributions are not statistically different from other theoretical distributions that also fit the observed distributions at specific alpha levels.

Table 1. Precipitation per event groups.

Group	Months
1	August, October
2	January, February, March, June
3	April, May
4	July, September, November, December

Table 2. Interarrival time groups.

Group	Months
1	January, March, April, July, September, December
2	February, May, October, November
3	June
4	August

Figure 3. Probability distributions for precipitation per event of grouped months.

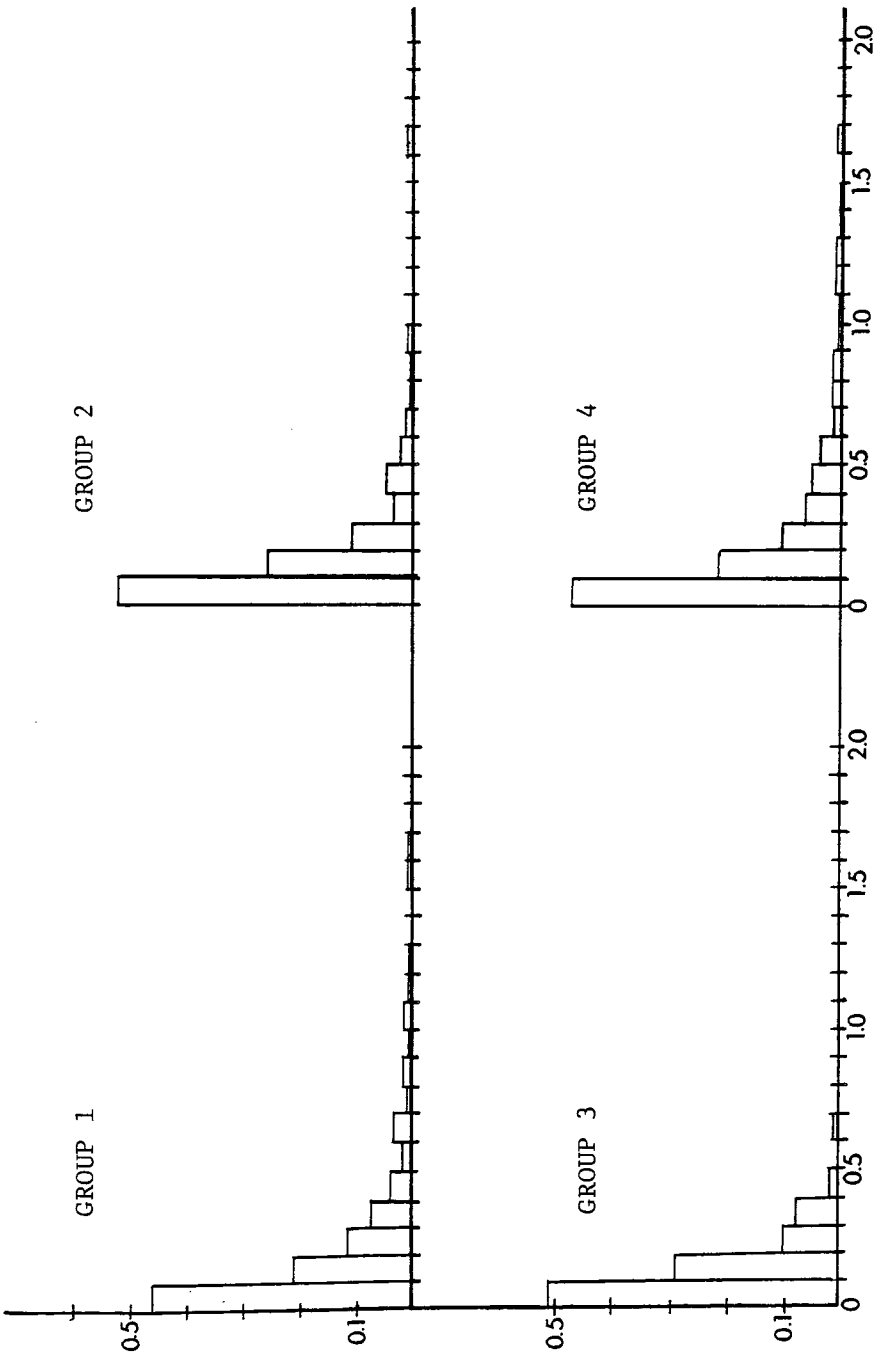

Figure 4. Probability distributions for interarrival time of grouped months.

The Kolmogorov-Smirnov (K-S) test, using a 0.05 alpha level or 0.95 confidence interval, was used to verify the acceptance of a gamma distribution. The theoretical distributions were compared to the observed distributions. The results of the test, shown in Table 3, indicated that gamma distributions compared favorably, i.e., "a good fit" with the actual distributions.

The theoretical gamma distributions were used in a model that stores density functions, for the grouped event characteristics. Random numbers between 0 and 1 were generated, assigned a group number, and compared to the stored CDF. The value of the CDF associated with each random number was used to build a "randomized" PDF and CDF for both event characteristics using the stored theoretical gamma distributions. A statistical was used to provide a verification of the observed and "randomized" theoretical distribution's "goodness of fit." The K-S test was again used to compare the distributions. The test results, shown in Table 4, indicated favorable correlations for all groups of both event characteristics. Therefore, the distributions for the amount of precipitation per event and the number of days between events are accepted as an accurate account of actual precipitation characteristics occurring on the Black Mesa.

Runoff Model

The runoff model transforms generated grouped precipitation per event and interarrival time distributions to runoff which is stored in a designed reservoir. Daily evaporation and an irrigation demand are accounted.

Table 3. Kolmogorov-Smirnov (K-S) test results comparing the theoretical gamma distribution to the observed distribution.

Compares distributions for interarrival time and precipitation per event.

K-S TEST

Test Parameters:

Observed CDF = $F_n(x)$
Hypothesized CDF = $F(x)$ = gamma CDF
Maximum Difference = $F_n(x)-F(x)$

$$C_{.95,n} = \frac{1.36}{\sqrt{n}}$$

H_o: $F_n(x)$ has the same distribution as the hypothetical distribution $F(x)$
Accept H_o: MAX D $\leq C_{\alpha,n}$

	Group Number	MAX D = $F_n(x)-F(x)$	$C_{.95,n}$
INTERARRIVAL TIME			
	1	0.0349	0.0476
	2	0.0294	0.0654
	3	0.0325	0.1353
	4	0.0460	0.09148
PRECIPITATION PER EVENT			
	1	0.0257	0.0773
	2	0.0215	0.0634
	3	0.0242	0.0997
	4	0.0137	0.0583

Table 4. Kolmogorov-Smirnov (K-S) test results comparing the "randomized" gamma distribution to the observed distribution.

Compares distributions for interarrival time and precipitation per event.

K-S TEST

Test Parameters:

Observed CDF = $F_n(x)$
Hypothesized CDF = $F(x)$ = "Randomized" gamma CDF
Maximum Difference = $F_n(x)-F(x)$

$$C_{.95,n} = \frac{1.36}{\sqrt{n}}$$

H_o: $F_n(x)$ has the same distribution as the hypothetical distribution $F(x)$
Accept H_o: MAX D $\leq C_{\alpha,n}$

	Group Number	MAX D = $F_n(x)-F(x)$	$C_{.95,n}$
INTERARRIVAL TIME			
	1	0.0395	0.0476
	2	0.0271	0.06543
	3	0.0267	0.1353
	4	0.0483	0.0915
PRECIPITATION PER EVENT			
	1	0.0244	0.0772
	2	0.0262	0.0634
	3	0.0200	0.0997
	4	0.0214	0.0583

The rainfall and runoff data, used to derive runoff models for each catchment was collected from June 16, 1981 through October 31, 1981. The rainfall events monitored were between 0.05 and 1.425 inches. Despite the short length, this period was considered acceptable due to precipitation characteristics and to responses of the catchments to the varied events. Summer precipitation ranges from 50 to 65 percent of the annual total, and in some years, greatest precipitation generally occurs 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 (Smith, 1978). Therefore, the wettest and driest months are probably included in the observed data. It is acknowledged that winter storms are not represented in the data, and are generally lower intensity frontal storms. Runoff from the treated catchments for this type storm is not considered significantly affected by the storm's intensity. However, it should be noted that the average intensity observed varied between 0.028 and 1.60 inches per hour and the maximum 30 minute intensity varied between 0.05 and 1.60 inches per hour. Intensity ranges and rainfall amounts of this short record suggest that the data was representative of precipitation characteristics occurring throughout the year.

All precipitation events in this analysis are considered to be rain. The few winter precipitation events occurring as snow are considered insignificant when viewed on a yearly scale. An additional point is that snowfall will eventually contribute to runoff, considering the nature of the catchments and lower evaporation rates in the winter.

Antecedent moisture conditions of the salt-treated and FAC catchments are assumed to have negligible effects on runoff, since the impervious nature of the catchments has significantly reduced water holding capacity. Empirical results have shown that the pebble layer on the FAC catchment is capable of retaining large amounts of storm runoff, but the pebbles dry rapidly and therefore should not influence subsequent runoff events.

Seepage and sedimentation effects were also assumed minimal. Seepage from the Black Mesa reservoir system was minimized by a clay-rich soil lining. Sedimentation was virtually nonexistent on the treated catchments.

The empirical models were derived from rainfall-runoff relationships on the salt-treated catchment and the FAC catchment. The Statistical Package for the Social Sciences (SPSS) was used to run correlation analyses on the collected data. Runoff data from the salt-treated and FAC catchments were compared with regard to average intensity, maximum 30 minute intensity, and amount of storm precipitation. Bivariate and multiple correlation analyses indicated the best linear relation had similar r^2 values to that of the multiple correlation. Table 5 shows poor correlations between runoff and average intensity and between runoff and maximum 30 minute intensity. The correlations for both catchments for runoff versus the amount of storm precipitation were reasonably high. Table 6 shows the multiple correlation analyses of runoff from both catchments versus maximum 30 minute intensity and total storm precipitation.

Table 5. Results of SPSS bivariate analyses for runoff.

Correlations are shown for runoff from the salt-treated catchment, SRO, and from the fibreglass-asphalt-chipcoat catchment, FACRO, versus average intensity, AVGI, 30-minute intensity, I30, and storm precipitation, PPT.

Correlation	r^2
SRO vs. AVGI	0.02458
FACRO vs. AVGI	0.04576
SRO vs. I30	0.07793
FACRO vs. I30	0.08038
SRO vs. PPT	0.92321
FACRO vs. PPT	0.96969

Table 6. Results of SPSS multiple correlation analysis for SRO and FACRO versus I30 and PPT.

Correlation	r^2
SRO vs. I30 & PPT	0.92380
FACRO vs. I30 & PPT	0.97018

Although r^2 values were slightly higher for the multiple correlation analysis of both catchments, the simpler linear models gave essentially the same values. The choice of the linear model was further justified if one considers that additional error would be introduced from reading maximum 30 minute intensities from strip charts. The linear runoff models for the salt-treated and FAC catchments are illustrated in Figures 5 and 6, respectively.

The runoff model for the salt-treated catchment is:

$$QSALT = 0.62500\ (PPT) + 0.00895$$

PPT = amount of storm precipitation (in.)

QSALT = runoff from salt-treated catchment (in.)

and the runoff model for the FAC catchment:

$$QFAC = 0.55401\ (PPT) - 0.01210$$

PPT = amount of storm precipitation (in.)

QFAC = runoff from FAC catchment (in.)

Analysis of variance was performed to determine whether a significant difference existed between runoff from the two catchments. The F ratio was equal to 0.2718 and the critical value of F at the 0.10 alpha level was 2.86, therefore differences among the samples were not significant. Restated, the runoff from the salt-treated catchment is not significantly different from runoff from the FAC catchment at a 0.10 alpha level. This implies one runoff model could be derived to predict

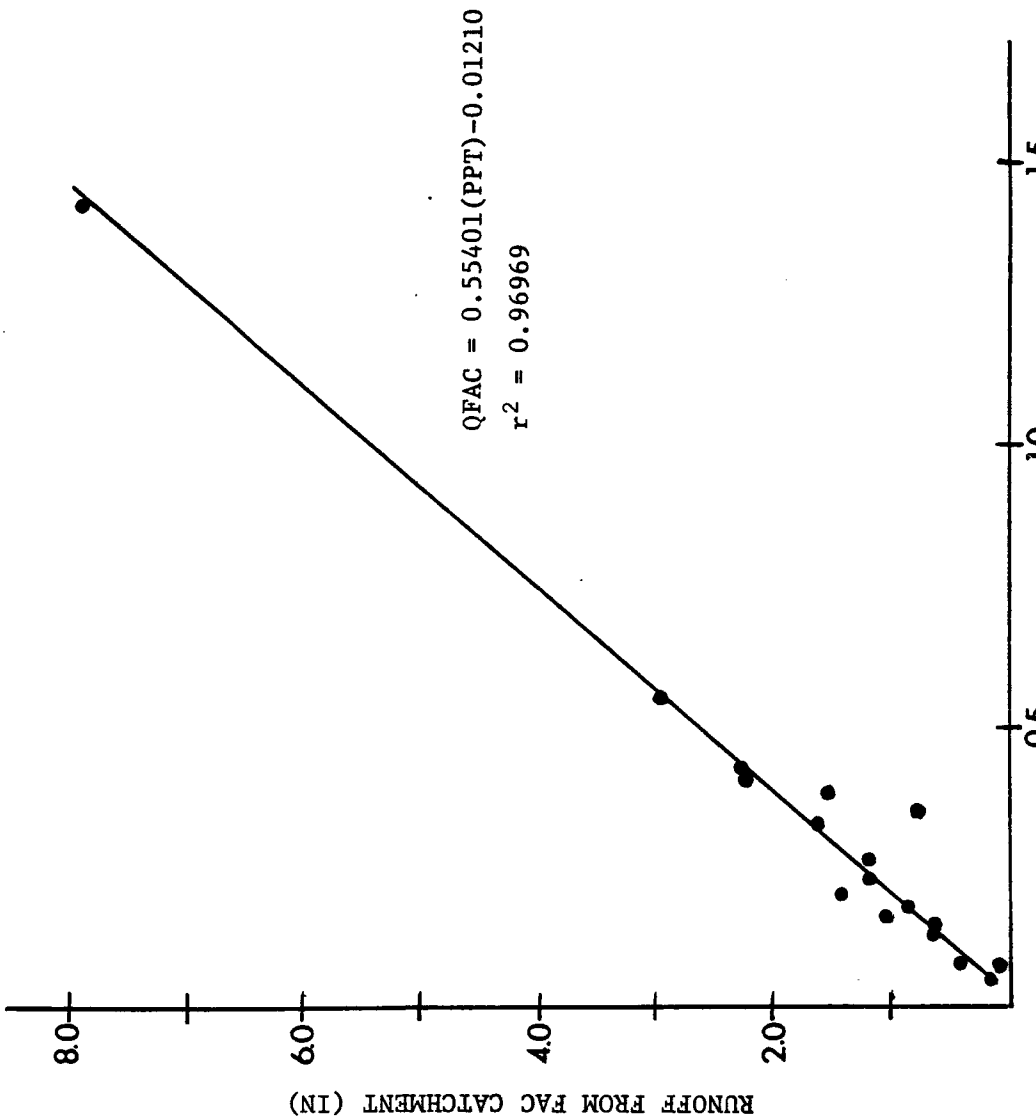

Figure 5. Runoff model for the salt-treated catchment.

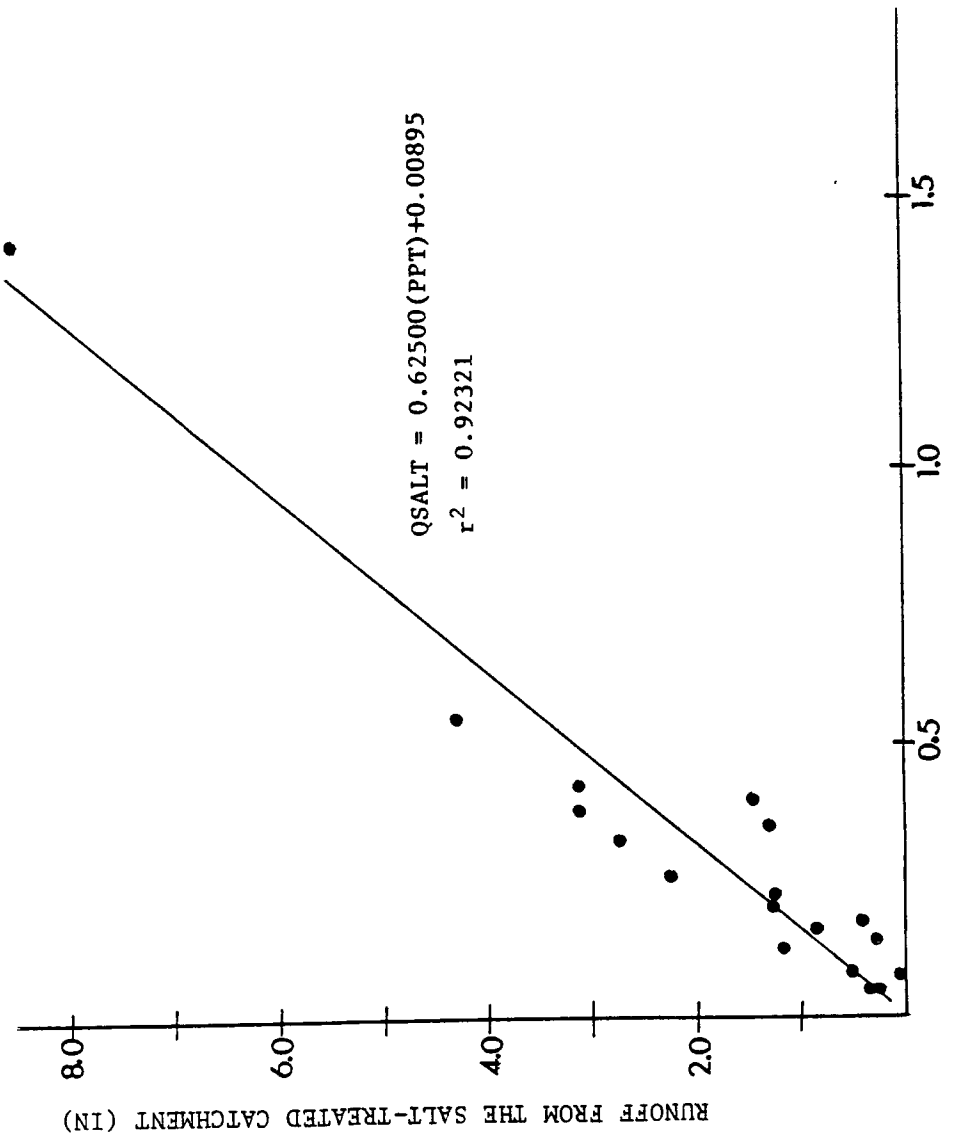

Figure 6. Runoff model for the FAC catchment.

runoff for both catchments, however, using two separate models did not pose any difficulties in the computer program and predicted runoff accurately.

Cluff and Frobel (1978) found runoff efficiencies for salt-treated catchments to range from 50-70 percent and in the range of 90-100 percent for FAC catchments. The average observed salt-treated runoff efficiency was 60.3 percent and in agreement with Cluff's estimate. However, the average observed FAC runoff efficiency was 49 percent, well below the estimated range. The difference may be explained, in part, by the thin gravel layer on the surface of the FAC catchment. Cooley et al. (1975) states that such a gravel layer reduces runoff efficiency by retaining part of the water which is then lost to evaporation.

A hypothetical reservoir was designed to store the harvested water using the function, $x = \sqrt[1.1]{y}$. By the definition of volumes by cross sections perpendicular to the y-axis, the function is rotated about the y-axis as shown in Figure 7. This yields the volume equation:

$$\text{Volume} = \int_b^a \pi \left(\sqrt[1.1]{y} \right)^2 dy$$

The volume in the reservoir was obtained by integrating between the limits, which are representative of the reservoir stage. The actual reservoir stage was obtained by subtracting 110 from the limits of integration.

The maximum reservoir volume was obtained by solving the integral using approximate limits of integration. By manipulating proposed limits of integration and substituting them into the original function,

Conversion to reservoir stage (ft)

120 = 10 ft
115 = 5 ft
110 = 0 ft

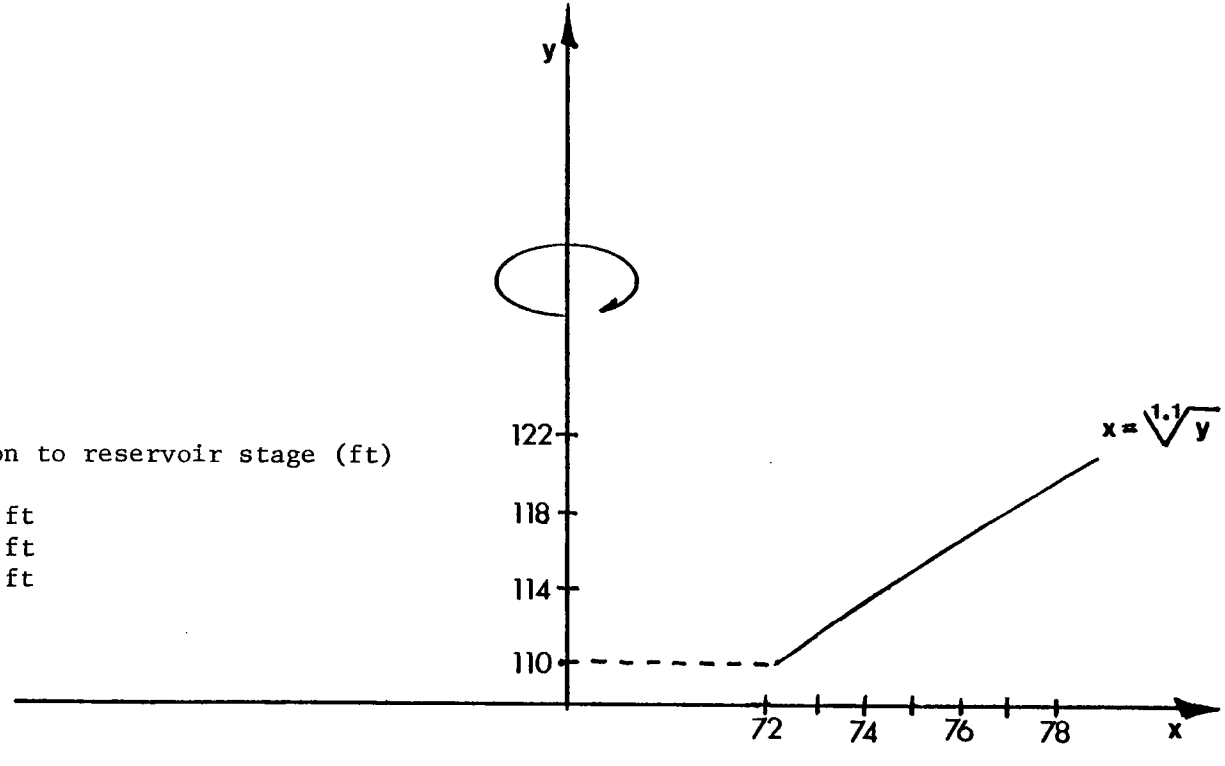

Figure 7. Reservoir function to be rotated about y-axis.

a preliminary reservoir was designed having suitable surface and bottom diameters and an appropriate stage. The reservoir's maximum stage is the difference between the limits of integration. Two different reservoir designs were determined after preliminary computer runs indicated an acceptable frequency of reservoir volume exceeding the maximum reservoir volume which implied overflow. Since optimal reservoir design was not a concern in this study, an arbitrary maximum frequency of overflows was selected. A more detailed procedure for determining the reservoir volume is discussed in following paragraphs.

Reservoir stage and volume were determined in two sections of the program: 1) reservoir outflow, and 2) inflow. The reservoir's outflow was updated for each day between events and inflow updated on days of events. Reservoir volume was given initially as half the maximum reservoir volume.

One outflow parameter, evaporation, was subtracted from the stage of the reservoir for each day between events. Monthly pan evaporation from Many Farms, Arizona was used since this was closest to the study site with annual records (Peabody Coal Co., 1982). The station is located 45 miles southeast of the study site at roughly the same elevation. A limited study suggests pan evaporation at the Black Mesa is within 5% of the Many Farms average (Fischer, 1976). Pan evaporation was adjusted for actual evaporation using a pan coefficient of 0.675 (Gay, 1981). PET values calculated using this coefficient are shown in Table 7. The reservoir stage, resulting from each daily evaporation loss, was found by solving the integral for the upper limit of integration, stage of the reservoir:

Table 7. Average daily lake evaporation for Black Mesa, Arizona.

Estimates are derived from monthly pan evaporation data multiplied by a pan coefficient of 0.675.

Month	Day of Year	Pan Evaporation (in./month)	Lake Evaporation (in./day) (COEFF=0.675)
January	1 - 31	1.00	0.02
February	32 - 59	3.40	-0.08
March	60 - 90	5.70	0.12
April	91 - 120	9.20	0.21
May	121 - 151	12.50	0.27
June	152 - 181	12.90	0.29
July	182 - 212	11.90	0.26
August	213 - 243	10.00	0.22
September	244 - 273	8.70	0.20
October	274 - 304	5.60	0.12
November	305 - 334	3.30	0.07
December	335 - 365	1.70	0.03

$$STRES = [(TRESV + 631243.01)/1.114759]^{0.354839}$$

STRES = Reservoir stage (FT)

TRESV = Reservoir volume, given initially as half the maximum reservoir volume (FT^3)

Note: The actual reservoir stage at any given time equals STRES minus the lower limit of integration.

Another outflow parameter was the daily irrigation demand during the approximate growing season. Powelson (1982) estimated Black Mesa's growing season from June 1 through October 1. The demand was varied for the growing season by percentages of the mean annual runoff. The total demand values used were broken down into daily demand values which were dependent on the growing season's varying monthly requirements. Powelson (1982) estimated the demand for June, July, August, and September as percentages of the total seasonal demand, 25, 35, 20, and 20 percent, respectively. STRES, accounting for daily evaporation loss was transformed into reservoir volume, TRESV, to accommodate irrigation demand, also in units of volume. The equation solving for reservoir volume is:

$$TRESV = (1.114759)\ STRES^{2.8181818} - 631243.01$$

TRESV = Reservoir volume (FT^3)

STRES = Reservoir stage (FT)

Reservoir volume was updated each day by subtracting irrigation demand and evaporation losses. Stage of the reservoir was then determined by solving back through the equation for STRES using the new

reservoir volume, TRESV. A reservoir stage less than zero indicated the reservoir was empty, and in this case, reservoir stage and volume were assigned a value of zero.

Inflow to the reservoir was total volume of runoff from the salt-treated and FAC catchments. Runoff values were expressed in inches of runoff over the catchments. Depth of runoff over the catchments was transformed into total runoff volume and added to the reservoir volume. This net volume was used again to solve for STRES, now the net reservoir stage. The net stage of the reservoir was compared to the maximum stage of the reservoir to determine whether overflow occurred. When this occurred, the net reservoir volume was assigned the value of the maximum reservoir volume.

The reservoir's stage and volume were cumulated through time. Year end totals of rainfall, runoff, and reservoir volumes were calculated and printed out for the 100 year period.

Probability and cumulative density functions were generated for the number of days during the growing season in which the reservoir was dry. The number of dry reservoir days corresponded to a particular class; the number of occurrences per class were stored for the 100 year period. Twenty-one classes were used having a lower limit of zero days and a maximum of 99 days. Dry reservoir days greater than 99 days were considered insignificant to this study and stored in the 21st class. The 1st class was for zero dry days throughout the year. Classes 2 through 21 were given a class interval size of 5. The probability density function, excluding zero dry days, was calculated by dividing the number

of occurrences per class by the 100 year period being simulated. This is the probability of a certain number of overflow reservoir days occurring in any 1 year. The CDF is the probability of occurrence of a particular number of reservoir overflows, or less, in any 1 year in 100 years.

A PDF and CDF were also generated for the volume of overflow per year. Volume of reservoir overflow was stored in classes ranging from zero to 30,000 cubic feet with a 1000 cubic foot class interval. The PDF was calculated by dividing the number of occurrences per class by 100 to obtain the probability of a particular volume of reservoir overflow in any 1 year.

Although the overflow volume distributions were not crucial in this study, they provide valuable information for determining a cost effective reservoir design since the reservoir design used in this study only approximates an optimal design.

MODEL SENSITIVITY

This chapter discusses the effects of varying different parameters within the runoff model to observe the reliability of having water stored during the growing season. Simulation was accomplished using two different reservoir designs having maximum stages of 5 and 10 feet. The total seasonal irrigation demand for each reservoir design was varied 25, 50, and 75 percent of the mean annual runoff. This chapter discusses each reservoir design, denoted 1 and 2, and the varied irrigation demand for each.

Reservoir 1 Model

The reservoir design used in this model had a 10 foot maximum stage and a maximum volume of 175419.1 cubic feet. The mean annual runoff from both the salt-treated and FAC catchments, was 232124.0 cubic feet.

Figure 8 is a bar graph representing probability density functions for the occurrence of dry reservoir days during the growing season. The different probability density functions are a result of varying the irrigation demand. Different demands were chosen as a function of mean annual runoff. Percentages of the mean annual runoff were assumed to be the total seasonal demand. Demands of 25, 50, and 75 percent of the mean annual runoff were used. Cases where the total seasonal demand is equal to 25, 50, and 75 percent of the mean annual runoff will be termed 25% MARO, 50% MARO, and 75% MARO. The demand throughout the season varied

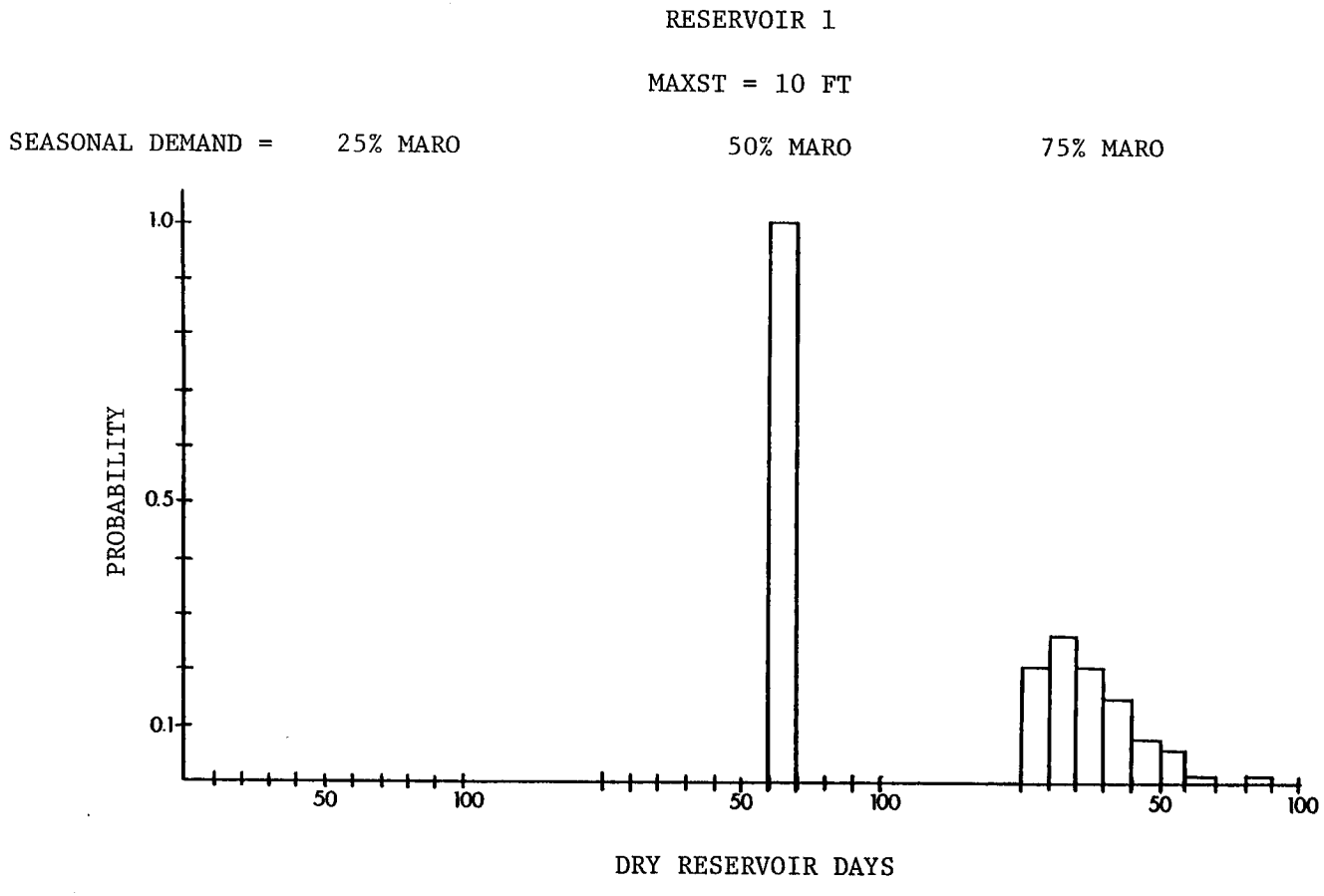

Figure 8. Probability distributions for dry reservoir days, Reservoir 1.

Excludes the class of zero dry reservoir days, i.e., the probability given dry reservoir days occur.

according to differing monthly requirements. An example representing the 25% MARO case for the 10 foot reservoir shows zero years in 100 having an occurrence of dry reservoir days. The classes of zero dry reservoir days were omitted in Figure 8 and new probability density functions generated to focus attention only on years when there had been days the reservoir was dry. Restated, given dry reservoir days, this is the probability of occurrence of a particular number of dry days occurring in any one year. Another example representing the 50% MARO case shows 1 year in 100 having an occurrence of dry reservoir days or a probability of 1.00 of having 70 dry days, or less, occurring in 100 years. Finer resolution found in the probability tables of Appendix B, show a probability is 1.00 of having 65 dry reservoir days, or less, occurring in 100 years. Class interval size for the probability tables is 5 days as opposed to 10 for the bar graphs. The bar graph shows that as irrigation demand increases, the probability of occurrence of more dry reservoir days per year increases. Conversely, as the irrigation demand decreases, fewer dry reservoir days will occur.

Figure 9 illustrates the occurrence frequency, of zero dry reservoir days. For example, the 25% MARO case for reservoir 1 shows zero years out of 100 have dry reservoir days.

Reservoir 2 Model

The design used for reservoir 2 had a 5 foot maximum stage and 84244.5 cubic feet maximum volume. The mean annual runoff was the same, 232124.0 cubic feet.

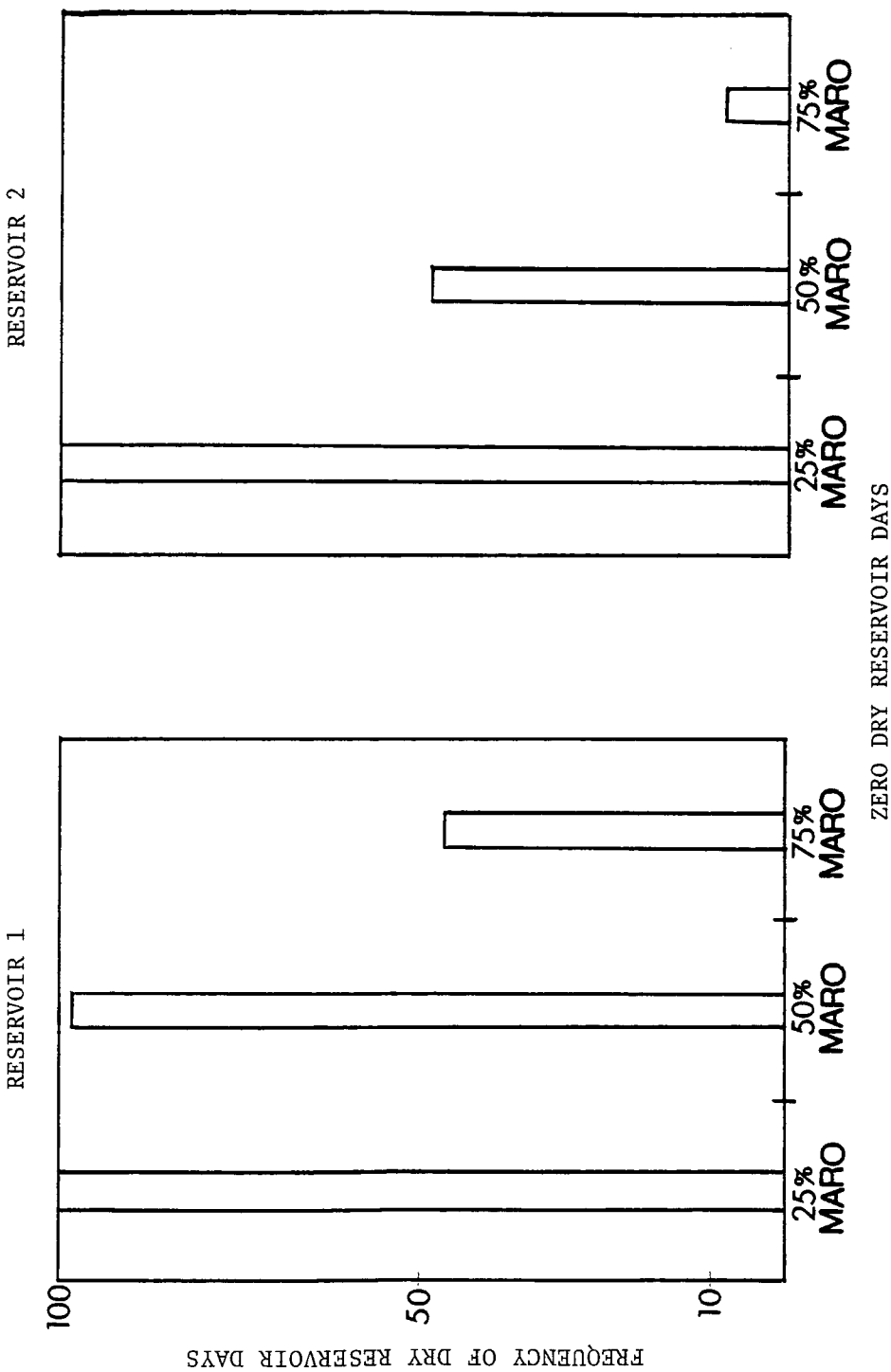

Figure 9. Frequency of years having zero dry reservoir days in 100 years.

Figure 9 represents the frequency of zero dry reservoir days occurring in 100 years and Figure 10 illustrates reservoir 2's probability distributions for dry reservoir days occurring during the growing season. The same procedure was used to vary the irrigation demand for this model as was used for the reservoir 1 model. The 25% MARO case for reservoir 2 also shows zero years in 100 having an occurrence of dry reservoir days. The probability of more dry reservoir days occurring per year increases as the total seasonal demand increases, and conversely the probability of fewer dry reservoir days occurring per year increases as the seasonal demand decreases. Tabular probability and cumulative probability distributions for dry reservoir days and reservoir overflow for the varied cases are listed in Appendices B and C, respectively. The CDF's represent the probability of a particular number of dry reservoir days or overflow reservoir days, or less, occuring in any one year.

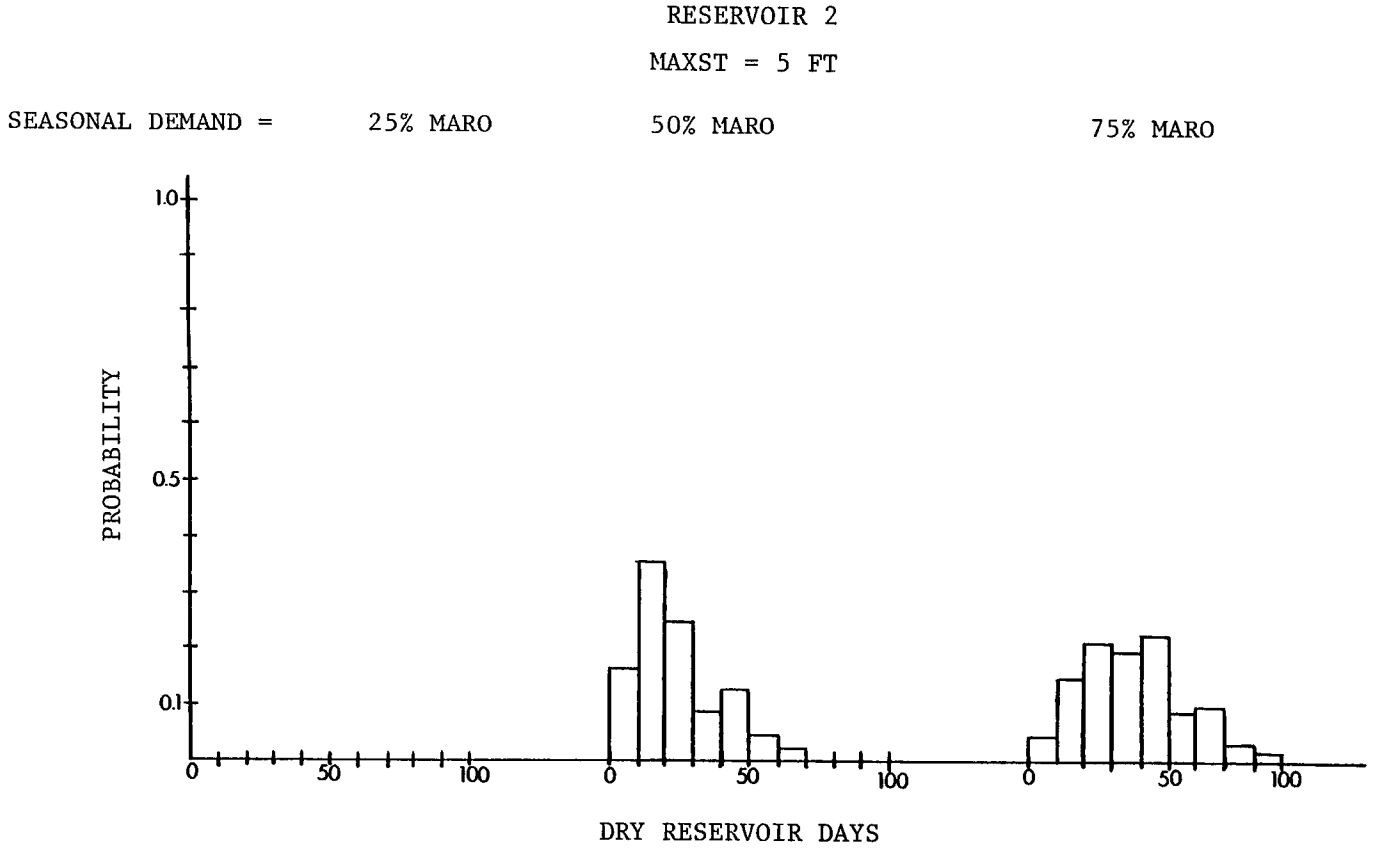

Figure 10. Probability distributions for dry reservoir days, Reservoir 2.

Excludes the class of zero dry reservoir days, i.e., the probability given dry reservoir days occur.

RESULTS AND DISCUSSION

This chapter discusses the results of the sensitivity analysis described in the previous chapter. The significance of the results for both reservoir designs, reservoir 1 having a 10 foot maximum stage and reservoir 2 having a 5 foot maximum stage, are outlined and compared.

The bar graphs, depicting probability distributions for both reservoir designs, indicate the reliability of meeting each year's irrigation demand. Reliability decreases as the total seasonal irrigation demand approaches the mean annual runoff. Probability trends are apparent through the distributions of dry reservoir days and distributions of overflow reservoir days. Graphs of dry reservoir day distributions and zero dry reservoir day frequencies are found in the previous chapter and tabular probability distributions are found in Appendices B and C.

Reservoir 1

Bar graphs and the distributions, representing total seasonal demand equal to 25, 50, and 75 percent of the mean annual runoff, reveal distinct probability trends of particular numbers of dry reservoir days occurring during the growing season of any one year. Important inferences are also derived from trends such as higher probabilities of occurrences for different class ranges for different cases.

The 75% MARO case, shown in Figures 8 and 9, reveals relatively higher probabilities in the approximate range 1-40 dry reservoir days. Dry reservoir days occurred 53 out of 100 years. The higher demand

intuitively suggests there will be more dry reservoir days per year. The higher probabilities within the range, 1-40 dry reservoir days, suggest on increased chance for a following day or days being dry, given that 1 dry reservoir day has occurred. Relatively more dry reservoir days per year, in turn, imply the possibility of the reservoir volume being persistently low. This conjecture is supported by the overflow distributions. Overflow occurred in only 28 out of 100 years. Overflow is a function of the size of the reservoir, but overflow days increase with decreased total seasonal demand indicating it is also a function of irrigation demand. The high frequency of dry reservoir days per year and the low frequency of overflow days, suggest the reservoir was persistently low. Storm events occurring after the reservoir becomes dry may be another possibility for the long sequences of dry reservoir days. Significant time before the first subsequent event, long interarrival times between subsequent events, and small precipitation amounts contribute to the inadequate reservoir volume needed to continually meet outflows.

The 50% MARO case, Figures 8 and 9, shows a radical decrease in the occurrences of dry reservoir days. Only 1 year in 100 had an occurrence of dry reservoir days and that year probably occurred in a drier than normal year. The decrease in demand was enough that the demand was essentially met over the long term. More water available to the reservoir suggests that subsequent precipitation is more likely to meet and sustain the daily evaporation loss and decreased irrigation demand.

The 25% MARO case, Figures 8 and 9, reveals that further decrease in the seasonal irrigation demand is substantial enough that no dry reservoir days occurred in 100 years, i.e., the seasonal demand was met each year. Even more water available implies more rapid replenishment of the reservoir.

Reservoir 2

The 75% MARO case, shown in Figures 9 and 10, had dry reservoir days 91 out of 100 years while outflow occurred in 84 out of the 100 years. A high frequency of dry reservoir days and overflow days has left little to infer about the relationship between a persistent low reservoir volume and the number of overflow and dry reservoir days. It can, however, be theorized that the reservoir remained low for sustained periods considering the expected increase in overflow and more dry reservoir days for the 5 foot reservoir as opposed to the 10 foot reservoir. Again, this case reveals higher probabilities in upper class ranges indicating occurrences of more consecutive dry days caused by a high demand and relatively less storage available.

Assumptions similar to the 75% MARO case, were made for the 50% MARO case and are depicted in Figures 9 and 10. Dry reservoir days occurred 51 out of 100 years while overflow occurred 95 out of 100 years. The highest probabilities occurred in relatively lower class ranges due to a decreased seasonal demand; i.e., more rapid replenishment of the reservoir implies a lesser chance of a series of dry reservoir days occurring.

The 25% MARO case, illustrated in Figures 9 and 10, shows the reservoir was not dry in any of the 100 years. In other words, the demand was met every year during the 100 year period.

Reservoir 1 and 2

The distributions and bar graphs have shown reliability to increase with a decreased irrigation demand. However, when comparing both reservoir designs, reliability also becomes a function of reservoir size. The 75% cases have shown reliability of the 5 foot reservoir design is less than that of the 10 foot design. The smaller storage available resulted in more water lost and therefore, less water is available to meet and sustain the irrigation demand. The 50% MARO cases show the 10 foot reservoir to be far more reliable than the 5 foot reservoir. In fact, the demand for reservoir 1 was essentially met every year and the demand for reservoir 2 was approximately 50 percent reliable. The 25% MARO cases indicate the demand was met every year for both designs. This implies the smaller design would provide suitable storage to meet the irrigation demand and be a more cost effective storage design for the system.

SUMMARY AND CONCLUSIONS

This study presented a procedure to generate hydrologic characteristics of a specific area using computer simulation techniques. A stochastic precipitation model was used to simulate daily precipitation for extended periods and serve as the input for a deterministic runoff model.

The precipitation model used a 20 year precipitation record from Betatakin National Monument located near the study area in northeastern Arizona. Observed distributions for event characteristics, amount of precipitation per event and interarrival time between events, were statistically fitted to theoretical distributions. Using a random number generator and the theoretical distributions, a 100 year precipitation record was generated. Two statistically derived runoff models, representing rainfall-runoff relationships of water harvesting catchments, were combined with the precipitation model to determine stored water availability and reliability from the water harvesting agrisystem.

The runoff model accounted for daily evaporation loss and seasonal irrigation demand. The total seasonal irrigation demand was varied to observe the response on the volume of water stored in a reservoir. Two reservoir designs, 1 and 2, were used for observation. Reservoir 1 had a 10 foot maximum stage and reservoir 2 had a 5 foot stage.

Reliability of having stored water available to meet and sustain a seasonal irrigation demand is a function of appropriate reservoir

storage and the seasonal demand. The total seasonal demand was varied by percentages of the mean annual runoff. Demands of 25, 50, and 75 percent of the mean annual runoff (MARO) were used. For a demand of 75% MARO, reliability was higher using the 10 foot reservoir design. However, the frequency of dry reservoir days was significant. The reliability of meeting demand each year was 53 percent for reservoir 1 and only 9 percent for reservoir 2. Therefore, reservoirs 1 and 2 would probably not be suitable reservoir designs when the demand was for 75% MARO. The 50% MARO cases met the seasonal irrigation demand better than the 75 percent case. Reservoir 1 had a 99 percent reliability and reservoir 2 a 49 percent reliability. If a 50% MARO demand is desired, reservoir 1 would be chosen over reservoir 2. The 25% MARO cases revealed a different situation where the demand was met every year with 100 percent reliability. The indication is that there is a maximum reservoir size, above which more storage would be available than needed and the cost of providing this additional storage would outweigh the resultant benefits. A chosen 10 foot reservoir design would be overdesigning for the system, therefore, the smaller reservoir 2 would be a more cost effective design. If the reservoir design was too small, the frequency of overflow may be so great that usable water would be lost. However, as in the 25% MARO cases, for greatest reliability a relatively large catchment area may require a relatively small reservoir. The higher volumes of runoff would sustain the reservoir volume at shorter intervals to meet irrigation demand even though there would be a higher frequency of overflows. The overflow frequency and volume combined with the frequency of

dry reservoir days would permit an optimal system evaluation using proper cost-benefit techniques.

A modification of the study's model could be incorporated into an optimization program for reservoir and catchment size. Knowing precipitation patterns, a water harvesting system could be designed optimizing both reservoir design and catchment area for a given irrigation demand. Water availability information would result, from which appropriate crops could be determined.

If a study's objective was crop survival, another possible modification would be to model the number of consecutive dry reservoir days during the growing season to determine an optimal irrigation demand requirement. Given plant stress, their tolerance to a specific number of dry days could be determined and an irrigation schedule devised in conjunction with water availability.

Although the model used in this study is site specific, given adequate data, the procedure can be applied to other water harvesting systems. Given rainfall-runoff data for the catchment, a runoff model similar to this study's models can be developed statistically. Different storage designs could also be incorporated, whether it is a single or compartmented reservoir system.

APPENDIX A

PROGRAM LISTING OF THE PRECIPITATION-RUNOFF-STORAGE MODEL

```
&SUP    T=00004 IS ON CR00013 USING 00093 BLKS R=0000

FTN4
      PROGRAM MESA
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                                  C
C  THIS PROGRAM GENERATES GAMMA DISTRIBUTIONS FOR PRECIP/EVENT AND  C
C  INTERARRIVAL TIME AND THEN,USING A RANDOM NUMBER GENERATOR,A     C
C  PDF AND CDF IS GENERATED FOR EACH GROUP.                         C
C                                                                  C
C  A 100 YEAR RUNOFF MODEL IS ALSO INCLUDED. THE MODEL CALCULATES   C
C  RUNOFF FOR THE TWO CATCHMENTS USING THE SIMULATED PRECIPITATION  C
C  A SEASONAL IRRIGATION DEMAND,THROUGH A GIVEN SIZE RESERVOIR.     C
C                                                                  C
C  THE NUMBER OF DAYS THE RESERVOIR IS DRY IS OF PARTICULAR         C
C  IMPORTANCE,ESPECIALLY DURING THE GROWING SEASON. FOR THIS        C
C  REASON,A PDF AND CDF ARE GENERATED FOR THE NUMBER OF DAYS        C
C  PER YEAR THE RESERVOIR IS DRY.                                   C
C                                                                  C
C  THE PROGRAM'S OUTPUT INCLUDES; 1) GENERATED GAMMA DISTRIBUTIONS  C
C  FOR PRECIP/EVENT AND INTERARRIVAL TIME, 2) 100 YEARS OF TOTAL    C
C  YEARLY RAINFALL, 3) 100 YEARS OF TOTAL RUNOFF, 4) TOTAL RESER-   C
C  VOIR VOLUME, 5) PDF AND CDF OF DAYS PER YEAR THE RESERVOIR IS    C
C  DRY, 6) PDF AND CDF OF DAYS PER YEAR THE RESERVOIR OVERFLOWS,    C
C  7) PDF AND CDF OF VOLUME PER YEAR OF RESERVOIR OVERFLOW.         C
C                                                                  C
C  NOTE: INITIAL RESERVOIR VOLUME(TRESV) AND INITIAL RESERVOIR      C
C  STAGE(STRES) CHANGE FOR THE DIFFERENT RESERVOIR DESIGNS          C
C                                                                  C
C  MONTHLY DEMAND VALUES(DDEM) CHANGE FOR THE DIFFERENT TOTAL       C
C  SEASONAL DEMANDS.                                                C
C                                                                  C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC


      REAL PPT(40,8),GAMMA(8),K(8),LAM(8),PROB2(40,8),INTER(70,4)
      REAL MAXST,MAXVOL,MARO,PDF1(21),CDF1(21)
      REAL INTVAL,YRESV(100),TR(100),YVRO(100),PROB1(70,4)
      REAL PDF2(31),CDF2(31),VOL(100),OVERV(100)
      INTEGER GN,W,R(8),DRY(100),SSH(21),SSL(21),DAYS(21)
      INTEGER SSL1(31),SSH1(31),SPILL(31),ODAYS(21),OVER(100)


      DATA GAMMA/2.5518,2.2290,2.1258,1.8714,1.4295,1.2537,1.0410,
     .1.2974/

      DATA K/0.3493,0.3981,0.4172,0.4733,0.6266,0.7295,1.089,0.7041/

      DATA LAM/0.0581,0.0574,0.0437,0.1329,3.1874,5.0508,8.9073,
     .3.7121/

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                                  C
C     GAMMA IS FROM THE GAMMA FUNCTION                              C
C     LAM IS LAMDA FROM A GAMMA DISTRIBUTION                        C
```

```
0055  C     K IS ALSO FROM A GAMMA DISTIBUTION                              C
0056  C                                                                    C
0057  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0058
0059  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0060  C                                                                    C
0061  C     VARIABLE LIST                                                  C
0062  C                                                                    C
0063  C     INTER-THE ARRAY STORES THE INTERARRIVAL TIME DISTIBUTION       C
0064  C     PPT-THE ARRAY THAT STORES THE PPT/EVENT DISTRIBUTION           C
0065  C     K IS A PARAMETER USED TO CALCULATE A GAMMA DISTIBUTION         C
0066  C     PROB1 STORES THE INTERARRIVAL TIMES                            C
0067  C     PROB2 STORES THE PPT/EVENT VALUES                              C
0068  C     SVRO=VOLUME OF RUNOFF SUMMED                                   C
0069  C     RAIN=AMOUNT OF RAINFALL/EVENT (IN)                             C
0070  C     TRAIN=RAIN SUMMED FOR THE YEAR (IN)                            C
0071  C     YVRO=YEARLY VOLUME OF RUNOFF (FT**3)                           C
0072  C     YRESV=YEARLY RESERVOIR VOLUME ARRAY                            C
0073  C     TR=TOTAL YEARLY RAIN (IN)                                      C
0074  C     TRESV=TOTAL RESERVOIR VOLUME (FT**3)                           C
0075  C     TVRO=TOTAL VOLUME OF RUNOFF (FT**3)                            C
0076  C     QFAC=RUNOFF OVER THE FAC CATCHMENT (FT)                        C
0077  C     QSALT=RUNOFF OVER THE SALT CATCHMENT (FT)                      C
0078  C     STRES=STAGE OF RESERVOIR (SEE COMMENTS) (FT)                   C
0079  C     EVAP=AVERAGE MONTHLY EVAPORATION (IN)                          C
0080  C     STEVAP=AMOUNT OF EVAPORATION BETWEEN EVENTS (FT)               C
0081  C     DEMAND=IRRIGATION DEMAND-A PERCENTAGE OF MEAN ANNUAL RUNOFF    C
0082  C     MAXVOL=MAXIMUM RESERVOIR STORAGE                               C
0083  C     MAXST=MAXIMUM RESERVOIR STAGE (FT)                             C
0084  C     RO=SUM OF ANNUAL RUNOFF VALUES                                 C
0085  C     MARO=MEAN ANNUAL RUNOFF                                        C
0086  C     OVERV=COUNTER FOR OVERFLOW VOLUME                              C
0087  C     OVER=COUNTER FOR NUMBER OF OVERFLOW DAYS                       C
0088  C     ODAYS=STORES NUMBER OF OCCURENCES PER CLASS OF OVERFLOW DAYS    C
0089  C     DAYS=STORES NUMBER OF OCCURENCES PER CLASS OF DRY RESERVOIR     C
0090  C          DAYS                                                      C
0091  C     DRY=COUNTER FOR NUMBER OF DRY RESERVOIR DAYS THROUGHOUT        C
0092  C         EACH DAY                                                   C
0093  C     CD=CLASS FOR NUMBER OF DRY RESERVOIR DAYS                      C
0094  C     DD=CLASS FOR NUMBER OF OVERFLOW DAYS                           C
0095  C     ED=CLASS FOR VOLUME OF OVERFLOW CLASS                          C
0096  C                                                                    C
0097  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0098
0099  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0100  C                                                                    C
0101  C     N ARE THE GROUP NUMBERS FOR MONTHS THAT WERE FOUND TO BE       C
0102  C     STATISTICALLY THE SAME                                         C
0103  C                                                                    C
0104  C     SUBSCRIPTS 1 THROUGH 4 ARE FOR INTERARRIVAL TIME GROUPS        C
0105  C     SUBSCRIPTS 5 THROUGH 8 ARE FOR PRECIP/EVENT GROUPS             C
0106  C                                                                    C
0107  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0108
0109        CD=0.
0110        ICAL=0
```

```
0111          I1=0
0112          I2=1571
0113          LP=6
0114          TRESV=(GIVEN AS ONE HALF THE MAXIMUM RESERVOIR VOLUME)
0115          STRES=(GIVEN AS ONE HALF THE MAXIMUM RESERVOIR STAGE)
0116
0117
0118  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0119  C                                                                       C
0120  C      CALCULATE THE INTERARRIVAL DISTRIBUTION FOR THE 4 GROUPS         C
0121  C                                                                       C
0122  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0123
0124          DO 30 N=1,4
0125          R1=LAM(N)/GAMMA(N)
0126          R2=K(N)-1.
0127          Z=0
0128          DO 10 I=1,70
0129          DO 20 J=1,100
0130          X=FLOAT(J)/100.+FLOAT(I-1)
0131          Z=Z+R1*((LAM(N)*X)**R2)*EXP(-LAM(N)*X)
0132    20    CONTINUE
0133          INTER(I,N)=Z
0134    10    CONTINUE
0135
0136          DO 15 I=1,70
0137          INTER(I,N)=INTER(I,N)/Z
0138
0139    15    CONTINUE
0140    30    CONTINUE
0141
0142
0143  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0144  C                                                                       C
0145  C      CALCULATE THE PPT/EVENT DISTRIBUTION FOR THE 4 GROUPS            C
0146  C                                                                       C
0147  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0148
0149          DO 60 M=5,8
0150
0151          R1=LAM(M)/GAMMA(M)
0152          R2=K(M)-1
0153          Z=0
0154          DO 40 I=1,40
0155          DO 50 J=1,100
0156          X=FLOAT(J)/2000.+FLOAT(I-1)/20.
0157          Z=Z+R1*((LAM(M)*X)**R2)*EXP(-LAM(M)*X)
0158    50    CONTINUE
0159          PPT(I,M)=Z
0160    40    CONTINUE
0161
0162          DO 55 I=1,40
0163          PPT(I,M)=PPT(I,M)/Z
0164
0165    55    CONTINUE
0166    60    CONTINUE
```

```

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                                  C
C     THE RANDOM NUMBER IS GENERATED AND THE INTERARRIVAL TIME    C
C     (GAMMA) DISTRIBUTION IS SEARCHED FOR THE APPROPRIATE CLASS  C
C                                                                  C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      DO 1000 W=1,100
       IF(W.NE.1) GO TO 6000


  505 CALL RANDM(I1,I2,X)

      DO 510 II=1,70

        EVAP=0.
        STEVAP=0.
        DEMAND=0.


      KK=II
      ICAL=ICAL+1
       IF(ICAL.EQ.366) ITOT=1
       IF(ICAL.EQ.366) ICAL=1


      IF(ICAL.GE.1.AND.ICAL.LE.31) NN=1
      IF(ICAL.GE.32.AND.ICAL.LE.59) NN=2
      IF(ICAL.GE.60.AND.ICAL.LE.90) NN=3
      IF(ICAL.GE.91.AND.ICAL.LE.120) NN=4
      IF(ICAL.GE.121.AND.ICAL.LE.151) NN=5
      IF(ICAL.GE.152.AND.ICAL.LE.181) NN=6
      IF(ICAL.GE.182.AND.ICAL.LE.212) NN=7
      IF(ICAL.GE.213.AND.ICAL.LE.243) NN=8
      IF(ICAL.GE.244.AND.ICAL.LE.273) NN=9
      IF(ICAL.GE.274.AND.ICAL.LE.304) NN=10
      IF(ICAL.GE.305.AND.ICAL.LE.334) NN=11
      IF(ICAL.GE.335.AND.ICAL.LE.365) NN=12

C                                                                  C
C     FUNCTION STATEMENT DEVAP(JJ) DETERMINES DAILY VALUES OF      C
C     AVERAGE MONTHLY EVAPORATION                                  C
C                                                                  C
      JJ=NN
      S=DEVAP(JJ)
      EVAP=S

C                                                                  C
C     FUNCTION STATEMENT DDEM(JL) DETERMINES DAILY DEMAND VALUES   C
C                                                                  C
C                                                                  C
      JL=NN
      T=DDEM(JL)
      DEMAND=T
```

```
0223
0224  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0225  C                                                                              C
0226  C     NEXT SEQUENCE ACCOUNTS DAILY RESERVOIR VOLUME AND STAGE TO               C
0227  C     DETERMINE WHEN THE RESERVOIR IS DRY                                      C
0228  C                                                                              C
0229  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0230
0231        STEVAP=EVAP/12.
0232
0233  C     STAGE OF RESERVOIR MINUS EVAP
0234        STRES=STRES-STEVAP
0235        IF(STRES.LE.0.)GO TO 1100
0236
0237        STRES=STRES+110.
0238
0239  C     RESERVOIR VOLUME ACCOUNTING FOR EVAP
0240        TRESV=1.114759*STRES**2.8181818-631243.01
0241
0242  C     RESERVOIR VOLUME ACCOUNTING FOR BOTH EVAP AND DEMAND
0243        TRESV=TRESV-DEMAND
0244
0245  C     STAGE OF RESERVOIR ACCOUNTING FOR BOTH EVAP AND DEMAND
0246        STRES=((TRESV+631243.01)/1.114759)**0.354839
0247
0248  C     ACTUAL STAGE OF RESERVOIR
0249        STRES=STRES-110.
0250
0251  C     CHECK TO SEE IF RESERVOIR IS DRY
0252   1100 IF(STRES.LT.0.) STRES=0.
0253
0254  C     STRES=0 IMPLIES THE RESERVOIR IS DRY
0255        IF(STRES.EQ.0.) TRESV=0.
0256
0257  C     STORES THE NUMBER OF DAYS THE RESERVOIR IS DRY DURING THE
0258  C     GROWING SEASON (JUNE 1 THROUGH SEPT 30)
0259        IF(ICAL.GE.151.AND.ICAL.LE.273.AND.STRES.EQ.0.) DRY(W)=DRY(W)+1
0260
0261  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0262  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0263
0264  C                                                                              C
0265  C     DETERMINE THE INTERARRIVAL TIME GROUP NUMBERS (GN)                       C
0266  C                                                                              C
0267
0268        GN=1
0269        IF(NN.EQ.2.OR.NN.EQ.5.OR.NN.EQ.10.OR.NN.EQ.11) GN=2
0270        IF(NN.EQ.6) GN=3
0271        IF(NN.EQ.8) GN=4
0272
0273
0274        IF(INTER(KK,GN).GE.X) GO TO 515
0275    510 CONTINUE
0276    515 PROB1(KK,GN)=PROB1(KK,GN)+1.
0277        R(GN)=R(GN)+1
0278         IF(ITOT.EQ.1.) GO TO 6001
```

```
0279
0280  C                                                                      C
0281  C     DETERMINE THE PRECIP/EVENT GROUP NUMBERS (GN)                     C
0282  C                                                                      C
0283
0284   6000 GN=5
0285        IF(NN.EQ.1.OR.NN.EQ.2.OR.NN.EQ.3.OR.NN.EQ.6) GN=6
0286        IF(NN.EQ.4.OR.NN.EQ.5) GN=7
0287        IF(NN.EQ.7.OR.NN.EQ.9.OR.NN.EQ.11.OR.NN.EQ.12) GN=8
0288
0289
0290  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0291  C                                                                      C
0292  C     A RANDOM NUMBER IS GENERATED AND THE PRECIP/EVENT (GAMMA)        C
0293  C     DISTRIBUTION IS SEARCHED FOR THE APPROPRIATE CLASS               C
0294  C                                                                      C
0295  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0296
0297        CALL RANDM(I1,I2,X)
0298
0299
0300        DO 520 II=1,40
0301        KK=II
0302        IF(PPT(KK,GN).GE.X) GO TO 525
0303   520  CONTINUE
0304   525  PROB2(KK,GN)=PROB2(KK,GN)+1.
0305        R(GN)=R(GN)+1
0306
0307        RAIN=FLOAT(KK)/20.-0.025
0308
0309  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0310  C                                                                      C
0311  C     NEXT SEQUENCE ACCOUNTS RESERVOIR VOLUME RESULTING FROM           C
0312  C     RUNOFF INFLUX                                                    C
0313  C                                                                      C
0314  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0315
0316        QFAC=(0.55401*RAIN-0.01210)/12.
0317        QSALT=(0.62500*RAIN+0.0095)/12.
0318        TVRO=QFAC*328216.67+QSALT*230533.33
0319
0320  C     RESERVOIR VOLUME ACCOUNTING FOR RESERVOIR INFLUXES (RAINFALL
0321  C       FALLING DIRECTLY ON RESERVOIR AND RUNOFF)
0322        RAIN=RAIN/12.
0323        STRES=STRES+RAIN
0324         STRES=STRES+110.
0325        TRESV=1.114759*STRES**2.8181818-631243.01
0326
0327        TRESV=TRESV+TVRO
0328        SVRO=TVRO+SVRO
0329         RAIN=RAIN*12.
0330        TRAIN=TRAIN+RAIN
0331        MAXVOL=1.114759*(120. OR 115.)**2.8181818-1.114759*110.**2.8181818
0332        MAXST=(120. OR 115.)-110.
0333
0334  C     STAGE OF RESERVOIR ACCOUNTING FOR NEW RESERVOIR INFLUXES
```

```
0335        STRES=((TRESV+631243.01)/1.114759)**0.354839
0336
0337  C     ACTUAL STAGE OF RESERVOIR
0338        STRES=STRES-110.
0339
0340  C     GREATER THAN MAXST IMPLIES OVERFLOW
0341  C       OVERFLOW VOLUME
0342            IF(TRESV.GT.MAXVOL) VOL(W)=TRESV-MAXVOL
0343  C       OVERFLOW VOLUME CUMMULATION
0344            IF(TRESV.GT.MAXVOL) OVERV(W)=OVERV(W)+VOL(W)
0345
0346            IF(STRES.GT.MAXST) TRESV=MAXVOL
0347
0348  C     OCCURENCES OF OVERFLOW ACCUMULATED THROUGHOUT THE YEAR
0349        IF(STRES.GT.MAXST) OVER(W)=OVER(W)+1
0350        IF(STRES.GE.MAXST) STRES=MAXST
0351
0352         GO TO 505
0353
0354  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0355  C                                                                       C
0356  C     TOTAL VOLUME (TRESV) IN THE RESERVOIR FOR THE YEAR IS STORED      C
0357  C     IN ARRAY (YRESV)                                                  C
0358  C                                                                       C
0359  C     TOTAL RAIN FOR THE YEAR (TRAIN) STORED IN ARRAY (TR)              C
0360  C                                                                       C
0361  C     SUMMED VOLUME OF RUNOFF OVER THE YEAR STORED IN ARRAY (YVRO)      C
0362  C                                                                       C
0363  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0364
0365   6001 YRESV(W)=TRESV
0366        TR(W)=TRAIN
0367        YVRO(W)=SVRO
0368        SVRO=0.
0369        TRAIN=0.
0370        ITOT=0.
0371        IF(DRY(W).EQ.0) GO TO 222
0372
0373  C   CLASSIFY AND STORE THE NUMBER OF DRY RESERVOIR DAYS PER YEAR
0374        CD=FLOAT(DRY(W))*0.2+1.9999999
0375        ICD=IFIX(CD)
0376   222  IF(DRY(W).EQ.0) ICD=1
0377        IF(ICD.GT.21) ICD=21
0378        DAYS(ICD)=DAYS(ICD)+1
0379
0380  C   CLASSIFY AND STORE THE NUMBER OF RESERVOIR OVERFLOW DAYS PER YEAR
0381        DD=FLOAT(OVER(W))*0.2+1.9999999
0382        IDD=IFIX(DD)
0383        IF(OVER(W).EQ.0) IDD=1
0384        IF(IDD.GT.21) IDD=21
0385        ODAYS(IDD)=ODAYS(IDD)+1
0386
0387  C   CLASSIFY AND STORE THE NUMBER OF RESERVOIR OVERFLOW AMOUNTS PER YEAR
0388        ED=OVERV(W)*0.001+2.
0389        IED=IFIX(ED)
0390        IF(OVERV(W).EQ.0.) IED=1
```

```
0391          IF(IED.GT.31) IED=31
0392          SPILL(IED)=SPILL(IED)+1
0393
0394          RO=YVRO(W)+RO
0395          IF(W.EQ.100) MARO=RO/100.
0396
0397
0398    1000 CONTINUE
0399
0400
0401          WRITE(LP,3)
0402     3    FORMAT(1X,///,5X,"YEARLY VOLUME OF RUNOFF")
0403          WRITE(LP,1) (YVRO(W), W=1,100)
0404     1    FORMAT(//,17(6F10.1,//))
0405          WRITE(LP,4)
0406     4    FORMAT(1X,///,5X,"TOTAL RAIN PER YEAR")
0407          WRITE(LP,2) (TR(W), W=1,100)
0408     2    FORMAT(//,13(8F7.3,//))
0409          WRITE(LP,6)
0410     6    FORMAT(1X,///,5X,"YEARLY RESERVOIR VOLUME")
0411          WRITE(LP,7)(YRESV(W),W=1,100)
0412     7    FORMAT(//,17(6F10.1,//))
0413          WRITE(LP,8)
0414     8    FORMAT(1X,///,5X,"MEAN ANNUAL RUNOFF")
0415          WRITE(LP,9) MARO
0416     9    FORMAT(//,F10.1,/)
0417
0418
0419  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0420  C                                                                       C
0421  C      THE PDF AND CDF FOR THE THEORETICAL (INTERARRIVAL TIME) DIS-     C
0422  C      TRIBUTION IS GENERATED                                           C
0423  C                                                                       C
0424  C      THE AVERAGE OF EVENTS IN EACH GROUP IS COMPUTED                  C
0425  C                                                                       C
0426  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0427
0428          DO 1050 GN=1,4
0429          WRITE(LP,700)
0430     700  FORMAT(1X,///,30X,"DISTRIBUTION OF INTERARRIVAL TIME GROUP",
0431         .,//,5X,"INTERVAL",41X,"PDF",15X,"CDF")
0432          CDF=0
0433          PDF=0
0434          DO 125 I=1,70
0435          PDF=PROB1(I,GN)/R(GN)
0436          CDF=PDF+CDF
0437          WRITE(LP,701)I,PDF,CDF
0438     701  FORMAT(8X,I3,40X,F6.4,12X,F6.4)
0439     125  CONTINUE
0440    1050  CONTINUE
0441
0442
0443  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0444  C                                                                       C
0445  C      THE PDF AND CDF FOR THE THEORETICAL (PRECIP/EVENT) DIS-          C
0446  C      TRIBUTION IS GENERATED                                           C
```

```
0447  C                                                                      C
0448  C     THE AVERAGE OF EVENTS IN EACH GROUP IS COMPUTED                  C
0449  C                                                                      C
0450  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0451
0452        DO 2000 GN=5,8
0453        WRITE(LP,703)
0454   703  FORMAT(1X,///,30X,"DISTRIBUTION OF RAINFALL/EVENT FOR",
0455       ." GROUP ",//,14X,"INTERVAL",32X,"PDF",19X,"CDF")
0456
0457        CDF=0
0458
0459        DO 225 I=1,40
0460        INTVAL=FLOAT(I)/20.-.025
0461        PDF=PROB2(I,GN)/R(GN)
0462        CDF=PDF+CDF
0463
0464
0465        WRITE(LP,704)INTVAL,PDF,CDF
0466   704  FORMAT(14X,F5.3,33X,F6.4,15X,F6.4)
0467   225  CONTINUE
0468  2000  CONTINUE
0469
0470
0471  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0472  C                                                                      C
0473  C     THE PDF AND CDF FOR THE NUMBER OF DAYS THE RESERVOIR IS          C
0474  C     DRY DURING THE GROWING SEASON                                    C
0475  C                                                                      C
0476  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0477
0478        WRITE(LP,706)
0479   706  FORMAT(1X,///,30X,"DISTRIBUTION OF RESERVOIR BEING",
0480       ." DRY",//,10X,"INTERVAL",10X,"OCCURENCES",6X,"PDF",7X,"CDF")
0481        CDF=0.
0482
0483        DO 425  M=1,21
0484        IF(M.EQ.1) SSH(M)=0.
0485        IF(M.EQ.1) SSL(M)=0.
0486        IF(M.EQ.1) GO TO 415
0487         SSH(M)=M*4+(M-5)
0488         SSL(M)=SSH(M)-4
0489   415  PDF1(M)=FLOAT(DAYS(M))/100.
0490        IF(M.EQ.1) GO TO 420
0491        CDF1(M)=CDF1(M-1)+PDF1(M)
0492        GO TO 425
0493   420  CDF1(M)=PDF1(M)
0494   425  CONTINUE
0495
0496        DO 725 JK=1,21
0497
0498   725  WRITE(LP,765) SSL(JK),SSH(JK),DAYS(JK),PDF1(JK),CDF1(JK)
0499   765  FORMAT(8X,F6.2,1X,"-",1X,F4.2,8X,I4,T42,F7.5,T52,F7.5,/)
0500
0501
0502  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

```
0503  C                                                                      C
0504  C     THE PDF AND CDF FOR THE NUMBER OF DAYS THE RESERVOIR             C
0505  C     OVERFLOWS                                                        C
0506  C                                                                      C
0507  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0508
0509        WRITE(LP,806)
0510   806  FORMAT(1X,///,30X,"DISTRIBUTION OF DAYS OF RESERVOIR",
0511       ." OVERFLOW",//,10X,"INTERVAL",10X,"OCCURENCES",6X,"PDF",7X,"CDF")
0512
0513        CDF=0.
0514        DO 455 L=1,21
0515        IF(L.EQ.1) SSH(L)=0.
0516        IF(L.EQ.1) SSL(L)=0.
0517        IF(L.EQ.1) GO TO 445
0518         SSH(L)=L*4+(L-5)
0519         SSL(L)=SSH(L)-4
0520   445  PDF1(L)=FLOAT(ODAYS(L))/100.
0521        IF(L.EQ.1) GO TO 450
0522        CDF1(L)=CDF1(L-1)+PDF1(L)
0523        GO TO 455
0524   450  CDF1(L)=PDF1(L)
0525   455  CONTINUE
0526
0527        DO 735 LM=1,21
0528   735  WRITE(LP,775) SSL(LM),SSH(LM),ODAYS(LM),PDF1(LM),CDF1(LM)
0529   775  FORMAT(8X,F6.2,1X,"-",1X,F4.2,8X,I4,T42,F7.5,T52,F7.5,/)
0530
0531
0532  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0533  C                                                                      C
0534  C     THE PDF AND CDF FOR THE VOLUME OF RESERVOIR OVERFLOWS            C
0535  C                                                                      C
0536  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0537
0538        WRITE(LP,906)
0539   906  FORMAT(1X,///,30X,"DISTRIBUTION OF AMOUNT OF RESERVOIR",
0540       ." OVERFLOW",//,10X,"INTERVAL",10X,"OCCURENCES",6X,"PDF",7X,"CDF")
0541
0542        CDF=0.
0543
0544        DO 465 N=1,31
0545        IF(N.EQ.1) SSL1(N)=0
0546        IF(N.EQ.1) SSH1(N)=0
0547        IF(N.EQ.1) GO TO 466
0548
0549         SSH1(N)=(N-1)*1000
0550         SSL1(N)=SSH1(N)-999
0551   466  PDF2(N)=FLOAT(SPILL(N))/100.
0552        IF(N.EQ.1) GO TO 470
0553        CDF2(N)=CDF2(N-1)+PDF2(N)
0554        GO TO 465
0555   470  CDF2(N)=PDF2(N)
0556   465  CONTINUE
0557
0558        DO 745 NM=1,31
```

```
0559    745  WRITE(LP,785) SSL1(NM),SSH1(NM),SPILL(NM),PDF2(NM),CDF2(NM)
0560    785  FORMAT(8X,I7,1X,"-",1X,I7,6X,I4,T42,F7.5,T52,F7.5,7)
0561
0562         STOP
0563         END
0564   CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0565         FUNCTION DEVAP(JJ)
0566
0567         IF(JJ.EQ.1) DEVAP=0.02
0568         IF(JJ.EQ.2) DEVAP=0.08
0569         IF(JJ.EQ.3) DEVAP=0.12
0570         IF(JJ.EQ.4) DEVAP=0.21
0571         IF(JJ.EQ.5) DEVAP=0.27
0572         IF(JJ.EQ.6) DEVAP=0.29
0573         IF(JJ.EQ.7) DEVAP=0.26
0574         IF(JJ.EQ.8) DEVAP=0.22
0575         IF(JJ.EQ.9) DEVAP=0.20
0576         IF(JJ.EQ.10) DEVAP=0.12
0577         IF(JJ.EQ.11) DEVAP=0.07
0578         IF(JJ.EQ.12) DEVAP=0.03
0579
0580
0581         RETURN
0582         END
0583   CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
0584         FUNCTION DDEM(JL)
0585
0586         DDEM=0
0587         IF(JL.EQ.6) DDEM=(25% OF THE TOTAL DEMAND)
0588         IF(JL.EQ.7) DDEM=(35% OF THE TOTAL DEMAND)
0589         IF(JL.EQ.8) DDEM=(20% OF THE TOTAL DEMAND)
0590         IF(JL.EQ.9) DDEM=(20% OF THE TOTAL DEMAND)
0591         RETURN
0592         END
0593
```

APPENDIX B

PROBABILITY DISTRIBUTIONS FOR DRY RESERVOIR DAYS

RESERVOIR 1

25% MARO MAX STAGE = 10 FT

Distribution of Reservoir Being Dry

Interval	Occurrences	PDF	CDF
1.00-5.00	0	0.000	0.000
6.00-10.00	0	0.000	0.000
11.00-15.00	0	0.000	0.000
16.00-20.00	0	0.000	0.000
21.00-25.00	0	0.000	0.000
26.00-30.00	0	0.000	0.000
31.00-35.00	0	0.000	0.000
36.00-40.00	0	0.000	0.000
41.00-45.00	0	0.000	0.000
46.00-50.00	0	0.000	0.000
51.00-55.00	0	0.000	0.000
56.00-60.00	0	0.000	0.000
61.00-65.00	0	0.000	0.000
66.00-70.00	0	0.000	0.000
71.00-75.00	0	0.000	0.000
76.00-80.00	0	0.000	0.000
81.00-85.00	0	0.000	0.000
86.00-90.00	0	0.000	0.000
91.00-95.00	0	0.000	0.000
96.00-100.00	0	0.000	0.000
	$\Sigma = 0$		

RESERVOIR 1

50% MARO MAX STAGE = 10 FT

Distribution of Reservoir Being Dry

Interval	Occurrences	PDF	CDF
1.00-5.00	0	0.000	0.000
6.00-10.00	0	0.000	0.000
11.00-15.00	0	0.000	0.000
16.00-20.00	0	0.000	0.000
21.00-25.00	0	0.000	0.000
26.00-30.00	0	0.000	0.000
31.00-35.00	0	0.000	0.000
36.00-40.00	0	0.000	0.000
41.00-45.00	0	0.000	0.000
46.00-50.00	0	0.000	0.000
51.00-55.00	0	0.000	0.000
56.00-60.00	0	0.000	0.000
61.00-65.00	1	1.000	1.000
66.00-70.00	0	0.000	1.000
71.00-75.00	0	0.000	1.000
76.00-80.00	0	0.000	1.000
81.00-85.00	0	0.000	1.000
86.00-90.00	0	0.000	1.000
91.00-95.00	0	0.000	1.000
96.00-100.00	0	0.000	1.000
	$\Sigma = 1$		

RESERVOIR 1

75% MARO MAX STAGE = 10 FT

Distribution of Reservoir Being Dry

Interval	Occurrences	PDF	CDF
1.00-5.00	5	0.094	0.094
6.00-10.00	6	0.113	0.207
11.00-15.00	8	0.151	0.358
16.00-20.00	6	0.113	0.471
21.00-25.00	6	0.113	0.584
26.00-30.00	5	0.094	0.678
31.00-35.00	6	0.113	0.791
36.00-40.00	2	0.038	0.829
41.00-45.00	2	0.038	0.867
46.00-50.00	2	0.038	0.905
51.00-55.00	1	0.019	0.924
56.00-60.00	2	0.038	0.962
61.00-65.00	0	0.000	0.962
66.00-70.00	1	0.019	0.981
71.00-75.00	0	0.000	0.981
76.00-80.00	0	0.000	0.981
81.00-85.00	0	0.000	0.981
86.00-90.00	1	0.019	1.000
91.00-95.00	0	0.000	1.000
96.00-100.00	0	0.000	1.000
	$\Sigma = 53$		

RESERVOIR 2

25% MARO MAX STAGE = 5 FT

Distribution of Reservoir Being Dry

Interval	Occurrences	PDF	CDF
1.00-5.00	0	0.000	0.000
6.00-10.00	0	0.000	0.000
11.00-15.00	0	0.000	0.000
16.00-20.00	0	0.000	0.000
21.00-25.00	0	0.000	0.000
26.00-30.00	0	0.000	0.000
31.00-35.00	0	0.000	0.000
36.00-40.00	0	0.000	0.000
41.00-45.00	0	0.000	0.000
46.00-50.00	0	0.000	0.000
51.00-55.00	0	0.000	0.000
56.00-60.00	0	0.000	0.000
61.00-65.00	0	0.000	0.000
66.00-70.00	0	0.000	0.000
71.00-75.00	0	0.000	0.000
76.00-80.00	0	0.000	0.000
81.00-85.00	0	0.000	0.000
86.00-90.00	0	0.000	0.000
91.00-95.00	0	0.000	0.000
96.00-100.00	0	0.000	0.000
	$\Sigma = 0$		

RESERVOIR 2

50% MARO MAX STAGE = 5 FT

Distribution of Reservoir Being Dry

Interval	Occurrences	PDF	CDF
1.00-5.00	5	0.098	0.098
6.00-10.00	3	0.059	0.157
11.00-15.00	11	0.216	0.373
16.00-20.00	7	0.137	0.510
21.00-25.00	7	0.137	0.647
26.00-30.00	5	0.098	0.745
31.00-35.00	4	0.078	0.823
36.00-40.00	0	0.000	0.823
41.00-45.00	3	0.059	0.882
46.00-50.00	3	0.059	0.941
51.00-55.00	1	0.020	0.961
56.00-60.00	1	0.020	0.981
61.00-65.00	0	0.000	0.981
66.00-70.00	1	0.020	1.000
71.00-75.00	0	0.000	1.000
76.00-80.00	0	0.000	1.000
81.00-85.00	0	0.000	1.000
86.00-90.00	0	0.000	1.000
91.00-95.00	0	0.000	1.000
96.00-100.00	0	0.000	1.000
	$\Sigma = 51$		

RESERVOIR 2

75% MARO MAX STAGE = 5 FT

Distribution of Reservoir Being Dry

Interval	Occurrences	PDF	CDF
1.00-5.00	2	0.022	0.022
6.00-10.00	2	0.022	0.044
11.00-15.00	6	0.066	0.110
16.00-20.00	7	0.077	0.187
21.00-25.00	7	0.077	0.264
26.00-30.00	12	0.132	0.396
31.00-35.00	9	0.099	0.495
36.00-40.00	8	0.088	0.583
41.00-45.00	9	0.099	0.682
46.00-50.00	11	0.121	0.803
51.00-55.00	3	0.033	0.836
56.00-60.00	4	0.044	0.880
61.00-65.00	4	0.044	0.924
66.00-70.00	4	0.044	0.968
71.00-75.00	2	0.022	0.990
76.00-80.00	0	0.000	0.990
81.00-85.00	0	0.000	0.990
86.00-90.00	1	0.011	1.000
91.00-95.00	0	0.000	1.000
96.00-100.00	0	0.000	1.000
	$\Sigma = 91$		

APPENDIX C

PROBABILITY DISTRIBUTIONS FOR RESERVOIR OVERFLOW DAYS

RESERVOIR 1

25% MARO MAX STAGE = 10 FT

Distribution of Reservoir Overflow

Interval	Occurrences	PDF	CDF
1.00-5.00	3	0.030	0.030
6.00-10.00	8	0.080	0.110
11.00-15.00	12	0.120	0.230
16.00-20.00	22	0.220	0.450
21.00-25.00	19	0.190	0.640
26.00-30.00	14	0.140	0.780
31.00-35.00	12	0.120	0.900
36.00-40.00	6	0.060	0.960
41.00-45.00	1	0.010	0.970
46.00-50.00	2	0.020	0.990
51.00-55.00	0	0.000	0.990
56.00-60.00	0	0.000	0.990
61.00-65.00	1	0.010	1.000
66.00-70.00	0	0.000	1.000
71.00-75.00	0	0.000	1.000
76.00-80.00	0	0.000	1.000
81.00-85.00	0	0.000	1.000
86.00-90.00	0	0.000	1.000
91.00-95.00	0	0.000	1.000
96.00-100.00	0	0.000	1.000
	$\Sigma = 100$		

RESERVOIR 1

50% MARO MAX STAGE = 10 FT

Distribution of Reservoir Overflow

Interval	Occurrences	PDF	CDF
1.00-5.00	12	0.154	0.154
6.00-10.00	15	0.192	0.346
11.00-15.00	15	0.192	0.538
16.00-20.00	22	0.282	0.820
21.00-25.00	8	0.103	0.923
26.00-30.00	4	0.051	0.974
31.00-35.00	1	0.013	0.987
36.00-40.00	0	0.000	0.987
41.00-45.00	0	0.000	0.987
46.00-50.00	0	0.000	0.987
51.00-55.00	1	0.013	1.000
56.00-60.00	0	0.000	1.000
61.00-65.00	0	0.000	1.000
66.00-70.00	0	0.000	1.000
71.00-75.00	0	0.000	1.000
76.00-80.00	0	0.000	1.000
81.00-85.00	0	0.000	1.000
86.00-90.00	0	0.000	1.000
91.00-95.00	0	0.000	1.000
96.00-100.00	0	0.000	1.000
	$\Sigma = 78$		

RESERVOIR 1

75% MARO MAX STAGE = 10 FT

Distribution of Reservoir Overflow

Interval	Occurrences	PDF	CDF
1.00-5.00	7	0.250	0.250
6.00-10.00	9	0.321	0.571
11.00-15.00	6	0.214	0.785
16.00-20.00	2	0.071	0.856
21.00-25.00	3	0.107	0.963
26.00-30.00	1	0.036	1.000
31.00-35.00	0	0.000	1.000
36.00-40.00	0	0.000	1.000
41.00-45.00	0	0.000	1.000
46.00-50.00	0	0.000	1.000
51.00-55.00	0	0.000	1.000
56.00-60.00	0	0.000	1.000
61.00-65.00	0	0.000	1.000
66.00-70.00	0	0.000	1.000
71.00-75.00	0	0.000	1.000
76.00-80.00	0	0.000	1.000
81.00-85.00	0	0.000	1.000
86.00-90.00	0	0.000	1.000
91.00-95.00	0	0.000	1.000
96.00-100.00	0	0.000	1.000
	$\Sigma = 28$		

RESERVOIR 2

25% MARO MAX STAGE = 5 FT

Distribution of Reservoir Overflow

Interval	Occurrences	PDF	CDF
1.00-5.00	2	0.020	0.020
6.00-10.00	4	0.040	0.060
11.00-15.00	16	0.160	0.220
16.00-20.00	15	0.150	0.370
21.00-25.00	19	0.190	0.560
26.00-30.00	19	0.190	0.750
31.00-35.00	12	0.120	0.870
36.00-40.00	7	0.070	0.940
41.00-45.00	3	0.030	0.970
46.00-50.00	2	0.020	0.990
51.00-55.00	0	0.000	0.990
56.00-60.00	0	0.000	0.990
61.00-65.00	1	0.010	1.000
66.00-70.00	0	0.000	1.000
71.00-75.00	0	0.000	1.000
76.00-80.00	0	0.000	1.000
81.00-85.00	0	0.000	1.000
86.00-90.00	0	0.000	1.000
91.00-95.00	0	0.000	1.000
96.00-100.00	0	0.000	1.000
	$\Sigma = 100$		

RESERVOIR 2

50% MARO MAX STAGE = 5 FT

Distribution of Reservoir Overflow

Interval	Occurrences	PDF	CDF
1.00-5.00	10	0.105	0.105
6.00-10.00	15	0.158	0.263
11.00-15.00	22	0.232	0.495
16.00-20.00	23	0.242	0.737
21.00-25.00	13	0.137	0.874
26.00-30.00	8	0.084	0.958
31.00-35.00	3	0.032	0.990
36.00-40.00	0	0.000	0.990
41.00-45.00	0	0.000	0.990
46.00-50.00	0	0.000	0.990
51.00-55.00	1	0.011	1.000
56.00-60.00	0	0.000	1.000
61.00-65.00	0	0.000	1.000
66.00-70.00	0	0.000	1.000
71.00-75.00	0	0.000	1.000
76.00-80.00	0	0.000	1.000
81.00-85.00	0	0.000	1.000
86.00-90.00	0	0.000	1.000
91.00-95.00	0	0.000	1.000
96.00-100.00	0	0.000	1.000
	$\Sigma = 95$		

RESERVOIR 2

75% MARO MAX STAGE = 5 FT

Distribution of Reservoir Overflow

Interval	Occurrences	PDF	CDF
1.00-5.00	10	0.119	0.119
6.00-10.00	19	0.226	0.345
11.00-15.00	23	0.274	0.619
16.00-20.00	16	0.191	0.810
21.00-25.00	9	0.107	0.917
26.00-30.00	5	0.060	0.977
31.00-35.00	1	0.012	0.989
36.00-40.00	0	0.000	0.989
41.00-45.00	0	0.000	0.989
46.00-50.00	1	0.012	1.000
51.00-55.00	0	0.000	1.000
56.00-60.00	0	0.000	1.000
61.00-65.00	0	0.000	1.000
66.00-70.00	0	0.000	1.000
71.00-75.00	0	0.000	1.000
76.00-80.00	0	0.000	1.000
81.00-85.00	0	0.000	1.000
86.00-90.00	0	0.000	1.000
91.00-95.00	0	0.000	1.000
96.00-100.00	0	0.000	1.000
	$\Sigma = 84$		

APPENDIX D

OBSERVED WATER HARVESTING DATA

Observed Water Harvesting Data From Black Mesa

	Event	Total Storm PPT (in)	Intensity (in/hr)	Max 30 Min. Inten. (in/hr)	Asphalt Runoff Over Basin (in)	Salt Runoff Over Basin (in)
1	6-30-81	0.35	0.074	0.23	0.082	0.133
2	7-1-81	0.075	0.023	0.10	0.012	0.01
3	7-8-81	0.38	0.051	0.74	0.157	0.315
4	7-11-81	0.08	0.160	0.16	0.047	0.055
5	7-12-81	0.26	0.049	0.20	0.122	0.228
6	7-13-81	0.125	0.50	0.50	0.068	0.120
7	7-15-81	0.425	1.01	1.01	0.232	0.315
8	7-16-81	0.16	0.28	0.28	0.107	0.09
9	8-1-81	0.05	0.10	0.10	0.020	0.03
10	8-22-81	0.175	0.06	0.15	0.088	0.046
11	8-23-81	0.40	1.60	1.60	0.227	0.15
12	8-25-81	0.20	0.16	0.40	0.143	0.13
13	8-28-81	0.05	0.05	0.05	0.018	0.038
14	9-4-81	0.325	0.43	0.60	0.165	0.277
15	9-6-81	0.14	0.079	0.10	0.067	0.032
16	9-15-81	0.55	0.730	0.73	0.30	0.433
17	9-23-81	0.225	0.056	0.25	0.122	0.129
18	10-1,2-81	1.425	0.130	0.30	0.792	0.858

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